Lepton number violation with Dirac neutrinos

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based on
J.H., PRD **88**, 076004 (2013),

J.H. and Werner Rodejohann,
EPL **103**, 32001 (2013).

Baryon and lepton number

- B and L classically conserved in the Standard Model.
- $B+L$ theoretically broken non-perturbatively: $\Delta(B+L)=6$.
- $B-L$ *globally* conserved.

Fate of fundamental $U(1)_{B-L}$ from **experiments**.
Linked to neutrino nature and matter–antimatter asymmetry.

- $B-L$ *locally* conserved after adding three ν_R.
  $\Rightarrow$ Neutrinos massive!

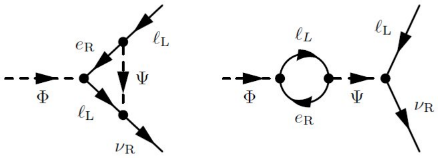
Three possibilities for (local) $U(1)_{B-L}$:

1. Unbroken $B-L$: Dirac neutrinos + neutrinogenesis.
2. Majorana $B-L$: $\Delta(B-L)=2$, Majorana ν + leptogenesis.
3. Dirac $B-L$: $\Delta(B-L)=n\neq 2$, Dirac ν + Dirac leptogenesis.

Unbroken $B-L$

Almost[1] never considered, but very simple:

- Neutrinos are Dirac, with Yukawa couplings $Y_\nu \sim m_\nu/\langle H\rangle \lesssim 10^{-11}$.
- Baryon asymmetry via neutrinogenesis:[2]
  - New scalars decay so that $\Delta(B-L) = \Delta L = 0$, but $\Delta L_{\rm left} = -\Delta L_{\rm right} \neq 0$.

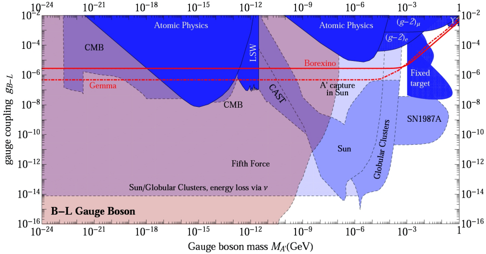


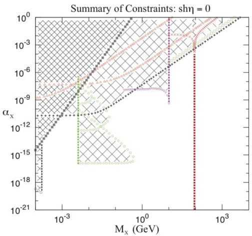
  - Right-handed ν_R not thermalized due to tiny Yukawas. $\Rightarrow$ Sphalerons only see $\Delta L_{\rm left}$, generate ΔB via $\Delta(B+L) = 6$!

[1] D. Feldman, P. Fileviez Perez, and P. Nath, 1109.2901.
[2] K. Dick, M. Lindner, M. Ratz, and D. Wright, hep-ph/9907562.

Signatures

- No $0\nu 2\beta$ or other $\Delta(B-L) \neq 0$ processes...
- Z' with tiny coupling $\alpha' \lesssim 10^{-50}$ or Stückelberg mass.
- $M_{Z'}/g'$ not connected to m_ν or leptogenesis $\Rightarrow$ no preferred scale!
- Limits, e.g. Williams et al., 1103.4556, Harnik et al., 1202.6073:





- Strong additional limits from $\overline{\nu}_R \gamma^\mu \nu_R Z'_\mu$ at BBN.[3]

$\Rightarrow$ Unbroken (local) $B-L$ perfectly valid!

[3] J.H., in preparation.

Majorana $B-L$

- New scalar $\phi_{B-L=2}$ to break $U(1)_{B-L}$ by two units.

$$\mathcal{L} \supset Y_\nu \, \overline{\nu}_R H L + \frac{1}{2} Y_R \, \overline{\nu}_R \nu_R^c \, \phi_{B-L=2}{}^* + \mathrm{h.c.}$$

- Spontaneous symmetry breaking gives mass matrix for (ν_L, ν_R^c):

$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu^T \langle H \rangle \\ Y_\nu \langle H \rangle & Y_R \langle \phi_{B-L=2} \rangle \end{pmatrix} .$$

- High scale $Y_R \langle \phi_{B-L=2} \rangle \gg Y_\nu \langle H \rangle$:
small seesaw Majorana mass for active neutrinos:

$$\mathcal{M}_\nu \simeq -\frac{\langle H \rangle^2}{\langle \phi_{B-L=2} \rangle} \, Y_\nu^T Y_R^{-1} Y_\nu .$$

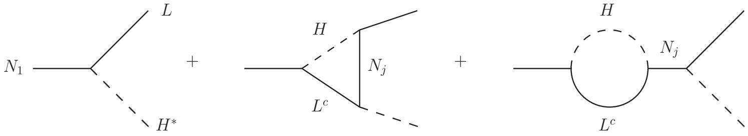
- Signature of Majorana $B-L$: neutrinoless double beta decay

$$(A, Z) \to (A, Z+2) + 2e^- \qquad \Leftrightarrow \qquad \Delta(B-L) = 2.$$

Majorana $B-L$: Leptogenesis

$$\mathcal{L} \supset Y_\nu \overline{\nu}_R H L + \frac{1}{2} Y_R \overline{\nu}_R \nu_R^c \phi_{B-L=2}{}^* + \text{h.c.}$$

- Heavy ($\mathcal{M}_R \simeq Y_R \langle \phi_{B-L=2} \rangle \gtrsim 10^8\,\text{GeV}$) Majorana neutrinos $N = \nu_R + \nu_R^c$ decay out-of-equilibrium in early Universe.



- If CP violated in loops: $\Gamma(N \to HL) \neq \Gamma(N \to H^* \overline{L})$
  $\Rightarrow$ Lepton asymmetry Δ_L!
- Sphalerons with $\Delta B = \Delta L = 3$ above $T \gtrsim \text{TeV}$ transfer Δ_L to baryon asymmetry Δ_B.

Dirac $B-L$

Break $B-L$, but by $n \neq 2$ units.[4]
$\Rightarrow$ Lepton number violating Dirac neutrinos.

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

$$\begin{aligned}
\mathcal{O}_{d=6}: &\quad \overline{\nu}_R^c \nu_R\, \overline{\nu}_R^c \nu_R \\
\mathcal{O}_{d=8}: &\quad |H|^2\, \overline{\nu}_R^c \nu_R\, \overline{\nu}_R^c \nu_R\,, \quad (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L)\, \overline{\nu}_R^c \nu_R\,, \quad F_Y^{\mu\nu} \overline{\nu}_R^c \sigma_{\mu\nu} \nu_R\, \overline{\nu}_R^c \nu_R \\
\mathcal{O}_{d=10}: &\quad (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L)\,(\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L)\,, \quad |H|^2 (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L)\, \overline{\nu}_R^c \nu_R\,, \\
&\quad F_Y^{\mu\nu} (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L)\, \overline{\nu}_R^c \sigma_{\mu\nu} \nu_R\,, \quad W_a^{\mu\nu} (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger \tau^a L)\, \overline{\nu}_R^c \sigma_{\mu\nu} \nu_R\,, \\
&\quad (\overline{u}_R d_R^c)(\overline{d}_R \tilde{H}^\dagger L)(\overline{\nu}_R^c \nu_R)\,, \dots \\
\mathcal{O}_{d=18}: &\quad (\overline{d}_R d_R^c\, \overline{u}_R^c u_R\, \overline{e}_R^c e_R)(\overline{d}_R d_R^c\, \overline{u}_R^c u_R\, \overline{e}_R^c e_R)\,, \dots \\
\mathcal{O}_{d=20}: &\quad \left[((\overline{D_\mu L})^c \tilde{H})(H^\dagger D_\nu L)\right]^2 \supset (\overline{e}_L^c W_\mu^+ W_\nu^+ e_L)(\overline{e}_L^c W^{+\mu} W^{+\nu} e_L)\,, \dots
\end{aligned}$$

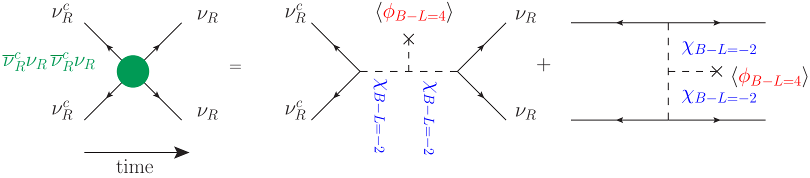
[4] Witten, hep-ph/0006332.

UV completion

- One scalar $\phi_{B-L=4}$ to break $B-L$, one scalar $\chi_{B-L=-2}$ as mediator.

$$\mathcal{L} \supset y_{\alpha\beta}\,\overline{L}_\alpha H \nu_{R,\beta} + \kappa_{\alpha\beta}\,\chi_{B-L=-2}\,\overline{\nu}_{R,\alpha}\nu^c_{R,\beta} + \text{h.c.}$$

- Neutrinos are Dirac (and $\Delta L = 2$ forbidden) if $\langle \chi_{B-L=-2}\rangle = 0$.
- Scalar potential $V \supset \mu\,\phi_{B-L=4}(\chi_{B-L=-2})^2 + \text{h.c.}$
- Lepton number violation $\Delta L = 4$ still possible![5]

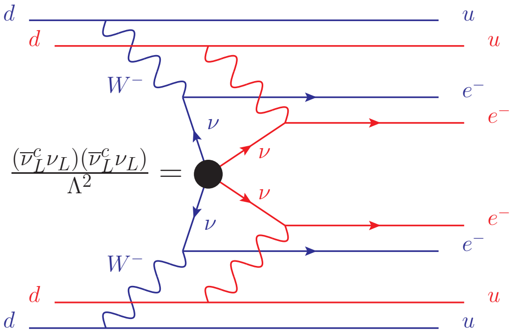


[5] J.H. and W. Rodejohann, EPL **103**, 32001 (2013) [arXiv:1306.0580].

$\Delta L = 4$ signature?

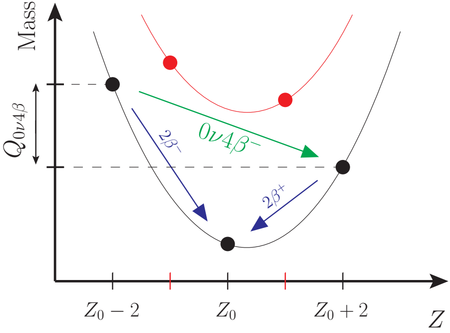
Neutrinoless quadruple beta decay $0\nu 4\beta$

$(\mathbf{A},\mathbf{Z}) \to (\mathbf{A},\mathbf{Z}+\mathbf{4}) + \mathbf{4}\,\mathbf{e}^-$ 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 here).

Candidates for nuclear $\Delta L = 4$ processes

	$Q_{0\nu4\beta}$	other decays	NA/%	experiment (2β)
$^{96}_{40}\mathrm{Zr} \to ^{96}_{44}\mathrm{Ru}$	0.629 MeV	$\tau_{2\nu2\beta} \simeq 2\times10^{19}$ y	2.8	NEMO
$^{136}_{54}\mathrm{Xe} \to ^{136}_{58}\mathrm{Ce}$	0.044 MeV	$\tau_{2\nu2\beta} \simeq 2\times10^{21}$ y	8.9	EXO/KZ/NEXT
$^{150}_{60}\mathrm{Nd} \to ^{150}_{64}\mathrm{Gd}$	2.079 MeV	$\tau_{2\nu2\beta} \simeq 7\times10^{18}$ y	5.6	NEMO
	$Q_{0\nu4\mathrm{EC}}$			
$^{124}_{54}\mathrm{Xe} \to ^{124}_{50}\mathrm{Sn}$	0.577 MeV	—	0.095	
$^{130}_{56}\mathrm{Ba} \to ^{130}_{52}\mathrm{Te}$	0.090 MeV	$\tau_{2\nu2\mathrm{EC}} \sim 10^{21}$ y	0.106	
$^{148}_{64}\mathrm{Gd} \to ^{148}_{60}\mathrm{Nd}$	1.138 MeV	$\tau_\alpha \simeq 75$ y	—	
$^{154}_{66}\mathrm{Dy} \to ^{154}_{62}\mathrm{Sm}$	2.063 MeV	$\tau_\alpha \simeq 3\times10^{6}$ y	—	

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- Existing 2β experiments can also look for $0\nu4\beta$!

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

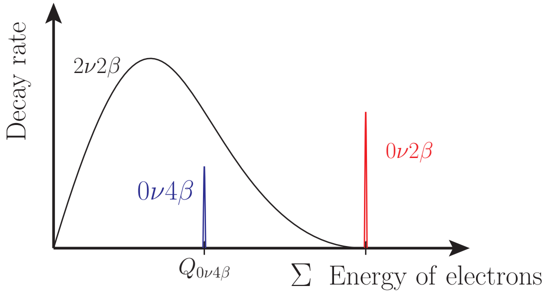
Decay channels:

- $^{150}_{60}\mathrm{Nd} \to {}^{150}_{62}\mathrm{Sm}$ via $2\nu 2\beta$ ($\tau_{1/2}^{2\nu 2\beta} \simeq 7 \times 10^{18}\,\mathrm{y}$):

$$0 < \sum E_{e,i} < 3.371\,\mathrm{MeV}.$$

- $^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$ via $0\nu 4\beta$:

$$\sum E_{e,i} = Q_{0\nu 4\beta} = 2.079\,\mathrm{MeV}.$$



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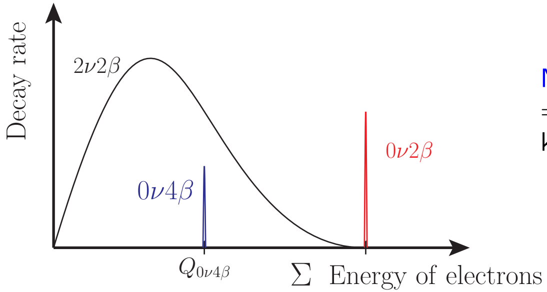
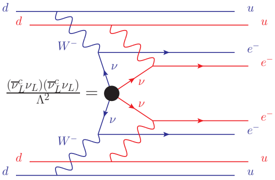


NEMO has **tracking**
⇒ Count electrons,
kill 2β background!

The catch: $0\nu4\beta$ rates

$(A,Z) \to (A,Z+4) + 4\,e^-$ 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 $|q| \sim p_\nu \sim 1\,\mathrm{fm}^{-1} \simeq 100\,\mathrm{MeV}$.

- Estimated rate in toy model unobservably small.
  Elaborate models with resonances overcome this???
- Resonant $0\nu4\mathrm{EC}$ possible?

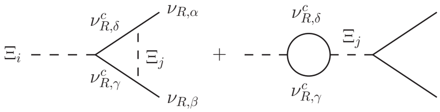
Dirac $B-L$: Leptogenesis

$\Delta L = 4$ easily relevant in early universe: new Dirac leptogenesis![6]

- Scalar potential $V(H,\phi,\chi) \supset -\mu\, \phi_{B-L=4} (\chi_{B-L=-2})^2$ breaks complex $\chi_{B-L=-2} = (\Xi_1 + i\,\Xi_2)/\sqrt{2}$ into two real scalars with mass

$$m_1^2 = m_c^2 - 2\mu\langle\phi_{B-L=4}\rangle\,, \qquad m_2^2 = m_c^2 + 2\mu\langle\phi_{B-L=4}\rangle\,.$$

- Heavy mediator scalar Ξ_j decays to $\nu_R\nu_R$ or $\overline{\nu}_R\overline{\nu}_R$ out-of-equilibrium in early Universe.



- *CP* violation requires *second* scalar $\chi_{B-L=-2}$.

Asymmetry in ν_R. ✓ How to translate to baryon asymmetry?

[6] J.H., PRD **88**, 076004 (2013) [arXiv:1307.2241].

Baryon asymmetry

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

- Dirac-Yukawa coupling $Y_\nu = m_\nu / \langle H \rangle$ too small to equilibrate ν_R...

Add second Higgs doublet H_2 with large Yukawa $\overline{L} H_2 \nu_R$:

- Neutrinophilic H_2 with small VEV $\langle H_2 \rangle \sim 1\,\mathrm{eV}$.
  $\Rightarrow$ Dirac neutrinos light with large Yukawas.[7]
- H_2 moves Y_{ν_R} to Y_{ν_L}.
- Sphalerons move Y_{ν_L} to Y_B.

$\Rightarrow$ Different from neutrinogenesis, similar to standard leptogenesis!

- Necessary thermalization of $\nu_R \Rightarrow N_\mathrm{eff} > 3$!
- $3.14 \lesssim N_\mathrm{eff} \lesssim 3.29$ depending on H_2^+ mass and Yukawa coupling.
- Specific collider signatures of neutrinophilic H_2.[7]

[7] Davidson and Logan, 0906.3335.

Summary

name	$\Delta(B-L)$	neutrino	BAU	signatures
Unbroken $B-L$	0	Dirac	neutrinogenesis	$Z'(?)$, $N_{\text{eff}} \simeq 3$
Majorana $B-L$	2	Majorana	leptogenesis	$0\nu2\beta$
Dirac $B-L$	>2, e.g. 4	Dirac	Dirac leptogenesis	$0\nu4\beta$, $N_{\text{eff}} \gtrsim 3.14$

- $B-L$ mystery: global, local, unbroken, broken by 2, 4, ... units?
- Currently testing: $\Delta L = 2$ via $0\nu2\beta$.
- In principle: $\Delta L = 4$ via $0\nu4\beta$;
  experimentally (and theoretically) challenging.
- Lepton number violation not synonymous with Majorana neutrinos.
- $\Delta L = 4$ lowest LNV of Dirac neutrinos.
- New Dirac leptogenesis ($3.14 \lesssim N_{\text{eff}} \lesssim 3.29$).

Phenomenology of LNV Dirac neutrinos

Quick summary:

- Even with Dirac neutrinos, we can have LNV.
- 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 processes:
  - LHC: $pp \to W^- W^- W^- W^- \ell^+ \ell^+ \ell^+ \ell^+ + X$,
  - Like-sign lepton collider: $e^- e^- \to W^- W^- W^- W^- \ell^+ \ell^+$.
- 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 predicting $3.14 \lesssim N_{\text{eff}} \lesssim 3.29$.[8]

[8] J.H., PRD **88**, 076004 (2013) [arXiv:1307.2241].

Comments on $0\nu4\beta$

- Background: electrons from $2\nu2\beta$ kick out two more e^-.
  $\Rightarrow$ 4 e^- with $\sum E_i \sim Q_{0\nu4\beta}$ possible.
- $0\nu4\beta$ 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 $\tau_{0\nu4\beta}$ (?)
- $0\nu6\beta$ etc. all involve beta-unstable nuclei.
  $\Rightarrow$ $0\nu2\beta$ and $0\nu4\beta$ somewhat unique.
- Very different $\Delta(B-L)=4$ decay: $4n \to 3p + 3e^-$, mimics $0\nu3\beta$.
  Candidate:

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

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

followed by the β^+ decay into ${}^{147}_{62}\mathrm{Sm}$ with half-life $24\,\mathrm{d}$.