Lepton number violation with *and without* Majorana neutrino masses

Julian Heeck

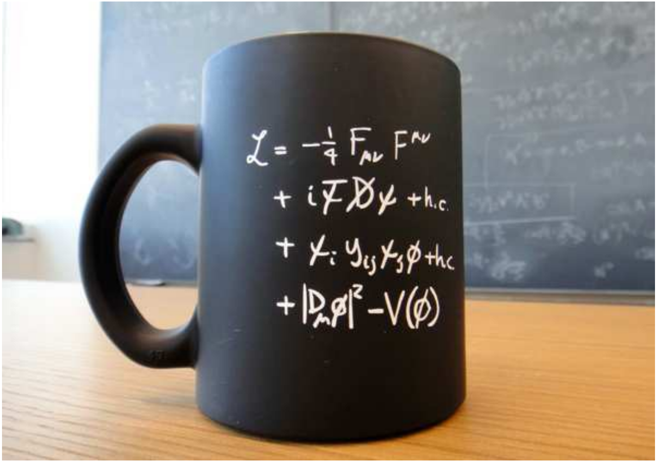
Université Libre de Bruxelles

15.03.2015 – Moriond – Electroweak Interactions

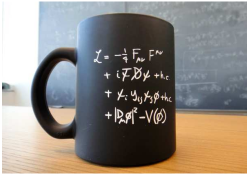
UNIVERSITÉ LIBRE DE BRUXELLES

Standard Model of Particle Physics

So simple and beautiful!



Standard Model of Particle Physics



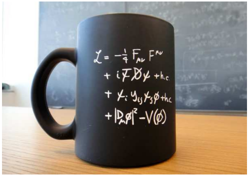
Small print:

- Gauge group $SU(3)_{\text{color}} \times SU(2)_{\text{isospin}} \times U(1)_{\text{hypercharge}}$;
  $\Rightarrow 8+3+1$ spin-1 bosons with field strength $F_{\mu\nu}$,
- Three copies of spin-$\frac{1}{2}$ Weyl fields (families/generations) in rep.

$$\Psi_{1,2,3} \sim \underbrace{(\mathbf{3},\mathbf{2},\tfrac{1}{6}) \oplus (\mathbf{3},\mathbf{1},-\tfrac{2}{3}) \oplus (\mathbf{3},\mathbf{1},\tfrac{1}{3})}_{\text{quarks}} \oplus \underbrace{(\mathbf{1},\mathbf{2},-\tfrac{1}{2}) \oplus (\mathbf{1},\mathbf{1},1)}_{\text{leptons}},$$

- One complex spin-0 field $\phi \sim (\mathbf{1},\mathbf{2},-\frac{1}{2})$ which breaks $SU(2) \times U(1) \to U(1)_{\text{EM}}$ via $\langle\phi\rangle \simeq 250$ GeV.
- About 18 free parameters, all measured as of 2013 (Brout–Englert–Higgs boson mass).

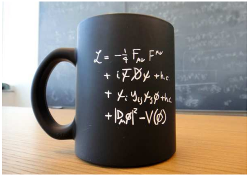
Standard Model of Particle Physics



even smaller print (shortcomings of the Standard Model):

- Neutrino mass and mixing?
- Dark matter?
- Origin of matter–antimatter asymmetry of our Universe?

Standard Model of Particle Physics



even smaller print (shortcomings of the Standard Model):

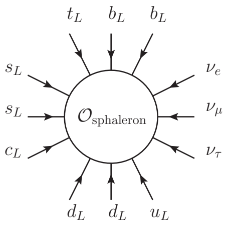
- Neutrino mass and mixing?
- Dark matter?
- Origin of matter–antimatter asymmetry of our Universe?

Actually *easy* to accommodate, but guided by what principle?

Symmetries of the Standard Model

A closer look at the mug:

- Baryon (B) and lepton number (L) classically conserved in the SM.
- $B+L$ theoretically broken non-perturbatively: $\Delta(B+L)=6$.
  - *Instanton*: tunneling at $T=0$, highly suppressed.
  - *Sphaleron*: thermal jump over barrier, fast for $T \gtrsim 100$ GeV.



- $B-L$ globally conserved in SM at quantum level.

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

Symmetry of the Standard Model: $B - L$

- $B - L$ globally conserved in SM.

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

One more comment from **theory**:

- $B - L$ locally conserved after adding three right-handed neutrinos

$$\nu_R \sim (\mathbf{1}, \mathbf{1}, 0)$$

  to cancel anomalies.
- Allows Yukawa coupling

$$\mathcal{L} \supset y_\nu \overline{L} \phi \nu_R + \text{h.c.} \to \underbrace{y_\nu \langle \phi \rangle}_{m_\nu} \overline{\nu}_L \nu_R + \text{h.c.}$$

$\Rightarrow$ Neutrinos automatically massive if we gauge $U(1)_{B-L}$!

Side Remark

With three ν_R, one can actually gauge the much larger non-anomalous[1]

$$U(1)_{B-L} \times U(1)_{L_e - L_\mu} \times U(1)_{L_\mu - L_\tau} \quad \Leftarrow \quad \text{for free!}$$

Flavored $U(1)$ subgroups can shed light on

- neutrino mixing (e.g. via texture zeros),[1]
- neutrino mass hierarchies,[2]
- flavor violation, e.g. $h \to \mu\tau$ in 2HDM,[3] ↙ Talk by Andreas Crivellin.
- lepton-non-universality in B-meson decays,[4]
- ...

$\Rightarrow$ Very simple gauge symmetry models to study lepton flavor!

[1] J.H., T. Araki, and J. Kubo, JHEP **1207** (2012) [arXiv:1203.4951].
[2] J.H. and W. Rodejohann, PRD **85**, 113017 (2012) [arXiv:1203.3117].
[3] J.H., M. Holthausen, W. Rodejohann, and Y. Shimizu, arXiv:1412.3671.
[4] J.H., A. Crivellin, and G. D'Ambrosio, PRL (2015) [arXiv:1501.00993], J.H., A. Crivellin, and G. D'Ambrosio, arXiv:1503.03477.

Back to $B-L$

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

1. Majorana $B-L$
   - $\Delta(B-L)=2$,
   - Majorana neutrinos, i.e. $\nu=\overline{\nu}$,
   - thermal leptogenesis.
2. Unbroken $B-L$
   - Dirac neutrinos, i.e. $\nu\neq\overline{\nu}$,
   - neutrinogenesis.
3. Dirac $B-L$
   - $\Delta(B-L)=n\neq 2$,
   - Dirac neutrinos,
   - Dirac leptogenesis.

Back to $B-L$

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

1. Majorana $B-L$
   - $\Delta(B-L)=2$,
   - Majorana neutrinos, i.e. $\nu=\overline{\nu}$,
   - thermal leptogenesis.
2. Unbroken $B-L$
   - Dirac neutrinos, i.e. $\nu\neq\overline{\nu}$,
   - neutrinogenesis.
3. Dirac $B-L$
   - $\Delta(B-L)=n\neq 2$,
   - Dirac neutrinos,
   - Dirac leptogenesis.

Majorana $B-L$

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

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

- 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:

$$\mathcal{M}_\nu \simeq -\frac{\langle H\rangle^2}{\langle\phi_{B-L=2}\rangle} Y_\nu^T Y_R^{-1} Y_\nu \sim 0.5\,\mathrm{eV}\left(\frac{10^{14}\,\mathrm{GeV}}{\langle\phi_{B-L=2}\rangle}\right).$$

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

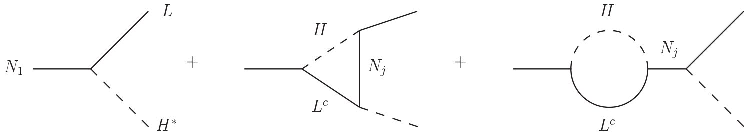
$$(A,Z) \to (A, Z+2) + 2e^- \qquad \Leftrightarrow \qquad \Delta(B-L) = 2.$$

- Low-scale seesaw has more signatures. ← J. Lopez-Pavon's talk.

Majorana $B-L$: Leptogenesis

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

- Heavy ($\mathcal{M}_R \simeq Y_R \langle \phi_{B-L=2} \rangle \gtrsim 10^8\,\mathrm{GeV}$) 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 $T \gtrsim 100$ GeV transfer Δ_L to baryon asymmetry $\Delta_B \propto \Delta_L$.

Majorana $B-L$: Summary

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

Very neat:

- Neutrinos massive, "automatically" small Majorana masses. ✓
- Matter–antimatter asymmetry. ✓
- (Making one of the ν_R light (keV) can give warm dark matter.[5] ✓)

[5] Upcoming white paper by M. Drewes, T. Lasserre, A. Merle, S. Mertens, J.H. et al.

Majorana $B - L$: Summary

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

Very neat:

- Neutrinos massive, "automatically" small Majorana masses. ✓
- Matter–antimatter asymmetry. ✓
- (Making one of the ν_R light (keV) can give warm dark matter.[5] ✓)

But:

- What if neutrinos turn out to be Dirac (like all other fermions)?
- Why should $B - L$ be broken by 2 units?
- Why broken at all?

[5] Upcoming white paper by M. Drewes, T. Lasserre, A. Merle, S. Mertens, J.H. et al.

Majorana $B - L$: Summary

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

Very neat:

- Neutrinos massive, "automatically" small Majorana masses. ✓
- Matter–antimatter asymmetry. ✓
- (Making one of the ν_R light (keV) can give warm dark matter.[5] ✓)

But:

- What if neutrinos turn out to be Dirac (like all other fermions)?
- Why should $B - L$ be broken by 2 units? $\Leftarrow$ *"Dirac $B - L$"*
- Why broken at all? $\Leftarrow$ *"Unbroken $B - L$"*

[5] Upcoming white paper by M. Drewes, T. Lasserre, A. Merle, S. Mertens, J.H. et al.

Back to $B-L$

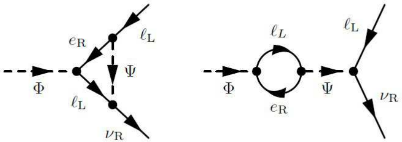
Three possibilities for (local) $U(1)_{B-L}$:

1. Majorana $B-L$
   - $\Delta(B-L)=2$,
   - Majorana neutrinos, i.e. $\nu=\overline{\nu}$,
   - thermal leptogenesis.
2. Unbroken $B-L$
   - Dirac neutrinos, i.e. $\nu\neq\overline{\nu}$,
   - neutrinogenesis.
3. Dirac $B-L$
   - $\Delta(B-L)=n\neq 2$,
   - Dirac neutrinos,
   - Dirac leptogenesis.

Unbroken $B - L$

Almost[6] never considered, but very simple:[7]

- Neutrinos are Dirac, with Yukawa couplings $Y_\nu \sim m_\nu/\langle H \rangle \lesssim 10^{-11}$.
- Matter–antimatter asymmetry via neutrinogenesis:[8]
  - New heavy scalar doublets decay so that $\Delta(B-L) = \Delta L = 0$, but $\Delta_L^{\text{left}} = -\Delta_L^{\text{right}} \neq 0$.



  - Right-handed ν_R not thermalized due to tiny Yukawas.
    $\Rightarrow$ Sphalerons only see Δ_L^{left}, generate $\Delta_B \propto \Delta_L^{\text{left}}$ via $\Delta(B+L) = 6$!

---

[6] D. Feldman, P. Fileviez Perez, and P. Nath, arXiv:1109.2901.
[7] J.H., PLB **739**, 256 (2014) [arXiv:1408.6845].
[8] K. Dick, M. Lindner, M. Ratz, and D. Wright, arXiv:hep-ph/9907562.

Signatures of Unbroken $B-L$

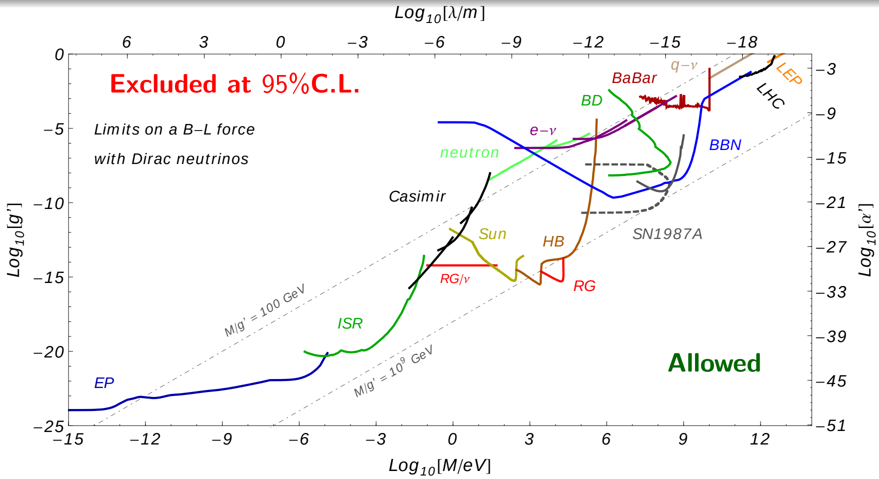
- No $0\nu 2\beta$ or other $\Delta(B-L) \neq 0$ processes. . .
- Massless Z' with tiny coupling $\alpha' \lesssim 10^{-50}$,
- or $M_{Z'} > 0$ with Stückelberg mass.
- $M_{Z'}/g'$ not connected to m_ν or leptogenesis $\Rightarrow$ no preferred scale!
- Limits from modified gravity, stellar energy losses, scattering/collider experiments, and Big Bang nucleosynthesis ($\overline{\nu}_R \gamma^\mu \nu_R Z'_\mu$).

$\Rightarrow$ Unbroken (local) $B-L$ perfectly valid![9]

- (For $\tau_{Z'} > \tau_{\text{Universe}}$, Z' could form dark matter via misalignment.)

[9] J.H., PLB **739**, 256 (2014) [arXiv:1408.6845].

The Money Shot



Applicable to any Z'_{B-L} (BBN, RG/ν, solid SN1987 depend on number of light ν_R).[10]

[10] J.H., PLB **739**, 256 (2014) [arXiv:1408.6845].

Back to $B-L$

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

1. Majorana $B-L$
   - $\Delta(B-L)=2$,
   - Majorana neutrinos, i.e. $\nu=\overline{\nu}$,
   - thermal leptogenesis.
2. Unbroken $B-L$
   - Dirac neutrinos, i.e. $\nu\neq\overline{\nu}$,
   - neutrinogenesis.
3. Dirac $B-L$
   - $\Delta(B-L)=n\neq 2$,
   - Dirac neutrinos,
   - Dirac leptogenesis.

Dirac $B-L$

Break $B-L$, but by $n \neq 2$ units.[11]
$\Rightarrow$ 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: $\Delta(B-L)=4$:

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

- $(U(1)_{B-L} \to \mathbb{Z}_4$ breakdown could stabilize dark matter.)

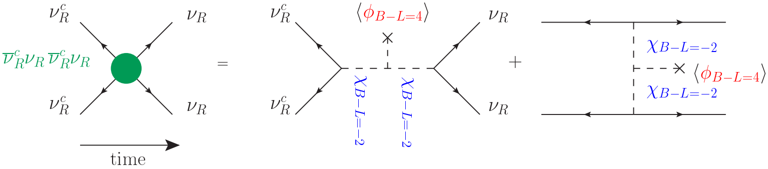
[11] $\Delta L = 0 \bmod n$ old idea, e.g. E. Witten, hep-ph/0006332.

UV Completion

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

$$\mathcal{L} \supset y\,\overline{L}\,H\,\nu_R + \kappa\,\chi_{B-L=-2}\,\overline{\nu}_R\,\nu_R^c + \text{h.c.}$$

- 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![12]



- Extension to left–right model can enhance rates.

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

Extension to Left–Right Model

- $U(1)_{B-L}$ easily embeddable into left–right symmetric models: $SU(2)_L \times U(1)_Y \to SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.
- ν_R now part of a doublet:

$$\Psi_L = (\nu_L,\, e_L)^T \sim (\mathbf{2}, \mathbf{1}, -1)\,,$$
$$\Psi_R = (\nu_R,\, e_R)^T \sim (\mathbf{1}, \mathbf{2}, -1)\,,$$
$$q_L = (u_L,\, d_L)^T \sim (\mathbf{2}, \mathbf{1}, 1/3)\,,$$
$$q_R = (u_R,\, d_R)^T \sim (\mathbf{1}, \mathbf{2}, 1/3)\,,$$
$$H = \begin{pmatrix} h_1^0 & h_1^+ \\ h_2^- & h_2^0 \end{pmatrix} \sim (\mathbf{2}, \overline{\mathbf{2}}, 0)\,.$$

- Typically introduce triplet $\delta \sim (\mathbf{1}, \mathbf{3}, -2)$ to break

$$SU(2)_R \times U(1)_{B-L} \xrightarrow{\langle\delta\rangle} U(1)_Y$$

at high scale and give mass to gauge bosons Z_R and $W_R^\pm$.
$\Rightarrow$ Left–right extension of Majorana $B-L$...

Left–Right Extension of Dirac $B-L$?

- Important part of simple model:

$$\mathcal{L} \supset y\,\overline{L}\,H\,\nu_R + \kappa\,\chi_{B-L=-2}\,\overline{\nu}_R\,\nu_R^c + \mu\,\phi_{B-L=4}(\chi_{B-L=-2})^2 + \text{h.c.}$$

- Extension to left–right straightforward:[13]

$$\chi_R = \frac{1}{\sqrt{2}}\begin{pmatrix} \chi_R^- & \chi_R^0 & 0 \\ \chi_R^{--} & 0 & \chi_R^0 \\ 0 & \chi_R^{--} & -\chi_R^- \end{pmatrix} \sim (\mathbf{1},\mathbf{3},-2)\,,$$

$$\phi_R = \frac{1}{\sqrt{6}}\begin{pmatrix} \phi_R^{++} & \sqrt{3}\phi_R^{+++} & \sqrt{6}\phi_R^{++++} \\ \sqrt{3}\phi_R^{+} & -2\phi_R^{++} & -\sqrt{3}\phi_R^{+++} \\ \sqrt{6}\phi_R^{0} & -\sqrt{3}\phi_R^{+} & \phi_R^{++} \end{pmatrix} \sim (\mathbf{1},\mathbf{5},4)\,.$$

- Couplings perfect (add χ_L and ϕ_L for LR parity):

$$\mathcal{L} \supset y\overline{\Psi}_L H \Psi_R + \kappa\,\overline{\Psi}_R \chi_R \Psi_R^c + \mu\,\mathrm{tr}\,[\chi_R\phi_R\chi_R] + \text{h.c.}$$

- Triplet *without* VEV, $SU(2)_R$ breaking via $\langle\phi_R\rangle$:

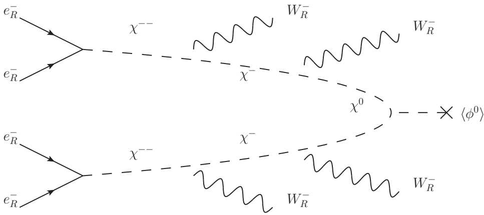
$$M^2_{W_R^\pm} = 2g_R^2\langle\phi_R^0\rangle^2\,, \qquad M^2_{Z_R} = 8\langle\phi_R^0\rangle^2(g_R^2 + 4g_{B-L}^2)\,.$$

[13] J.H., work in progress.

Phenomenology of LNV Dirac Neutrinos

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

- Collider processes:
  - LHC: $pp \to W^-W^-W^-W^-\ell^+\ell^+\ell^+\ell^+ + X$,
  - Like-sign lepton collider: $e^-e^- \to W^-W^-W^-W^-\ell^+\ell^+$.
- Nuclear decays ($0\nu4\beta$?).[14]
- Rare meson decays etc.?



All tough, many particles in final state and tiny rates![14]
(Even harder for $\Delta L > 4\dots$)

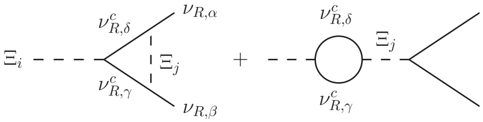
$\Delta L = 4$ can however easily be relevant in the early Universe
$\Rightarrow$ new *Dirac leptogenesis* mechanism![15]

---

[14] J.H. and W. Rodejohann, EPL **103**, 32001 (2013) [arXiv:1306.0580].
[15] J.H., PRD **88**, 076004 (2013) [arXiv:1307.2241].

Dirac $B-L$: Leptogenesis

- Two heavy mediator scalars $\chi^{j}_{B-L=-2} = (\Xi_j + i\,\Xi_j)/\sqrt{2}$ decay to $\nu_R\nu_R$ or $\overline{\nu}_R\overline{\nu}_R$ out-of-equilibrium in early Universe.



$\Rightarrow$ Asymmetry in ν_R:

$$\Delta_{\nu_R} \propto \frac{\Gamma\left(\Xi_i \to \nu_R\nu_R\right) - \Gamma\left(\Xi_i \to \nu^c_R\nu^c_R\right)}{\Gamma\left(\Xi_i \to \nu_R\nu_R\right) + \Gamma\left(\Xi_i \to \nu^c_R\nu^c_R\right)}\,.$$

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

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

Baryon Asymmetry

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

- Neutrinophilic H_2 with small VEV $\langle H_2\rangle \sim 1\,\mathrm{eV}$.[16]
  $\Rightarrow$ Dirac neutrinos light with large Yukawas.

$$\Delta_{\nu_R} \xrightarrow{H_2} \Delta_L \xrightarrow{\text{sphalerons}} \Delta_B\,.$$

$\Rightarrow$ Different from neutrinogenesis!

- 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.
- Planck 2015: $N_\mathrm{eff} = 3.15 \pm 0.23$ at 68% C.L.
- Specific collider signatures of neutrinophilic H_2.[17]

[16] Ma, PRL (2001), Wang, Wang, Yang, EPL (2006), Gabriel, Nandi, PLB (2007).
[17] Davidson and Logan, PRD **80** (2009) [arXiv:0906.3335].

Summary

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

- $B-L$ mystery: global, local, unbroken, broken by 2, 4, ... units?
- Currently testing: $\Delta L = 2$ via $0\nu2\beta$.
- $\Delta L \geq 4$ way more challenging (experimentally and theoretically),
- but easily relevant in the early Universe.

Backup

Stückelberg Mass

Mass for a $U(1)$ gauge boson without symmetry breaking:

- Introduce *real* scalar σ with gauge trafo $\sigma \to \sigma + M_{Z'}\theta(x)$.

$$\Delta\mathcal{L} = \tfrac{1}{2}\left(M_{Z'}Z'^{\mu} + \partial^\mu\sigma\right)\left(M_{Z'}Z'_\mu + \partial_\mu\sigma\right)$$

  is gauge invariant ($Z'_\mu \to Z'_\mu - \partial_\mu\theta$).
- Use gauge to set $\sigma(x) = 0$.
- Mass term $\frac{1}{2}M_{Z'}^2 Z'_\mu Z'^{\mu}$ is just gauge fixing, not breaking.

Abelian gauge bosons can have a mass without symmetry breaking.

- Connection to Higgs mechanism in formal limit

$$v_\Phi \to \infty\,, \qquad q_\Phi \to 0\,, \qquad M_{Z'} \propto q_\Phi v_\Phi = \text{const.}$$

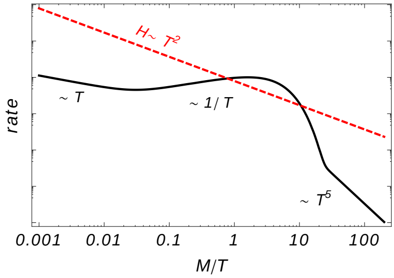
Big Bang Nucleosynthesis

Unbroken $B-L$:

- ν_R are light (Dirac neutrinos) $\rightarrow N_{\rm eff} \simeq 6$ for strong Z' interactions.
- Light Z' also contributes to $N_{\rm eff}$.
- BBN ($T \sim 1\,\mathrm{MeV}$) limit: $N_{\rm eff} < 4$ at 95% C.L.[18]

Thermally averaged rate via Z':

$$\langle \Gamma(\overline{f}f \leftrightarrow \overline{\nu}_R \nu_R)\rangle \propto \begin{cases} g'^4\, T\,, & M_{Z'} \ll T\,, \\ g'^2 \frac{M_{Z'}^2}{T}\,, & M_{Z'} \lesssim T\,, \\ \frac{g'^4}{M_{Z'}^4} T^5\,, & M_{Z'} \gg T\,. \end{cases}$$

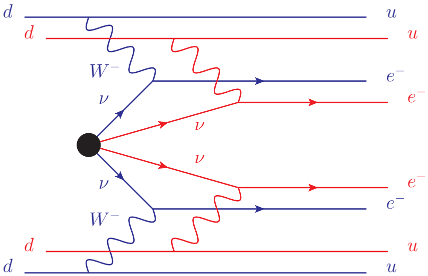


- Demand $\langle \Gamma(\overline{f}f \leftrightarrow \overline{\nu}_R \nu_R)\rangle < H(T) \sim T^2/M_{\rm Pl}$ "at" BBN.

[18] Mangano, Serpico, PLB (2011) [arXiv:1103.1261].

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

- Neutrinoless quadruple beta decay[19] $(A, Z) \to (A, Z+4) + 4\, e^-$
  e.g. via $\mathcal{O}_{\Delta L=4} = (\overline{\nu}_L^c \nu_L)^2/\Lambda^2$:

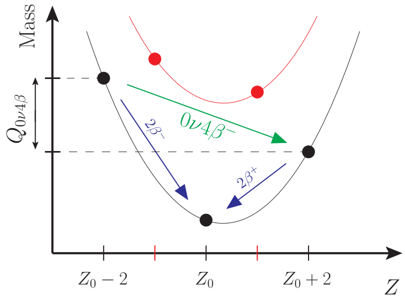


- Collider process $e^- e^- \to W^- W^- W^- W^- \ell^+ \ell^+$.
- Rare meson decays etc.?

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

Candidate Nuclei for $0\nu4\beta$

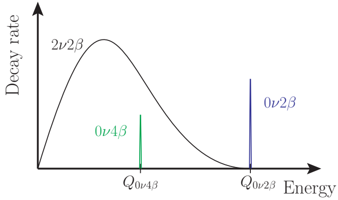
	$Q_{0\nu4\beta}$	competing decays	NA/%
${}^{96}_{40}\mathrm{Zr} \to {}^{96}_{44}\mathrm{Ru}$	0.629 MeV	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{19}$ y	2.8
${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ce}$	0.044 MeV	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{21}$ y	8.9
${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$	2.079 MeV	$\tau^{2\nu2\beta}_{1/2} \simeq 7 \times 10^{18}$ y	5.6



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

Decay channels:

- $^{150}_{60}\mathrm{Nd} \to {}^{150}_{62}\mathrm{Sm}$ via $2\nu2\beta$ ($\tau_{1/2}^{2\nu2\beta} \simeq 7\times 10^{18}\,\mathrm{y}$): the two 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 $0\nu4\beta$. Four electrons with continuous energy spectrum and summed energy $Q_{0\nu4\beta} = 2.079\,\mathrm{MeV}$ are emitted. In this special case, the daughter nucleus is α-unstable with half-life $\tau^{\alpha}_{1/2}({}^{150}_{64}\mathrm{Gd} \to {}^{146}_{62}\mathrm{Sm}) \simeq 2\times 10^{6}\,\mathrm{y}$.



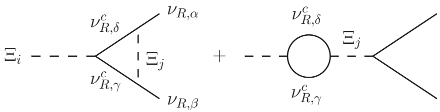
$0\nu4\beta$ kinematically allowed, but expected rates unobservable.

Dirac $B-L$: Leptogenesis

- 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 $\chi_{B-L=-2}$.

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

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

Baryon Asymmetry

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

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

- Neutrinophilic H_2 with small VEV $\langle H_2\rangle \sim 1\,\mathrm{eV}$.[20]
  $\Rightarrow$ Dirac neutrinos light with large Yukawas.
- H_2 moves Y_{ν_R} to Y_{ν_L}.
- Sphalerons move Y_{ν_L} to Y_B.

$\Rightarrow$ Different from neutrinogenesis!

- 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.[21]

[20] E. Ma, PRL **86** (2001), F. Wang, W. Wang, J. M. Yang, EPL **76** (2006), S. Gabriel and S. Nandi, PLB **655** (2007).
[21] Davidson and Logan, PRD **80** (2009) [arXiv:0906.3335].