TeV-scale lepton number violation: $0\nu\beta\beta$—decay, the origin of matter, and energy frontier probes

Phenomenology 2020 Symposium
May 4 - 6, 2020

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(in collaboration with Julia Harz, Michael Ramsey-Musolf, and Tianyang Shen)
New physics?

Why is there way more matter than antimatter in the observable universe?

Will we see BSM physics at the LHC?

Are neutrinos their own antiparticles?

Lepton Number Violation
\( \mathcal{L} = \# \text{leptons} - \# \bar{\text{leptons}} \)

TeV-scale

Deppisch, Harz & Hirsch (2013)
De Gouvêa et al. (2019)
Helo et al. (2013)
We study a simplified model: "Model O2" Peng, Ramsey-Musolf & Winslow (2015)

\[
\text{SM} + S: (1, 2, 1/2) \text{ and } F: (1, 1, 0) \\
m_F, m_S \sim \text{TeV} \\
\text{Minimal interactions}
\]
Goal of this talk

Leptogenesis

TeV-scale
LNV

$0\nu\beta\beta$–decay
Collider physics
Goal of this talk

Leptogenesis

TeV-scale LNV

$0\nu\beta\beta$–decay Collider physics
I. TeV-Scale and the Origin of matter

Leptogenesis

TeV-scale

LNV

$0\nu\beta\beta$—decay

Collider physics
Standard leptogenesis scenario

- SM + heavy right-handed, Majorana neutrino $N$: $\Delta \mathcal{L} \neq 0$

- Quantum corrections: $CP$–violation

- Sphaleron processes: $\Delta \mathcal{L} \to \Delta \mathcal{B}$
Standard leptogenesis scenario

- The leptogenesis process is described by Boltzmann equations:

\[
\frac{dY_N}{dz} = -\left(D + S\right)\left(Y_N - Y_N^{(eq)}\right)
\]

\[
\frac{dY_{B-L}}{dz} = -\epsilon D \left(Y_N - Y_N^{(eq)}\right) - W Y_{B-L}
\]

\[Y_X (N_X) : \text{normalized number density}\]
TeV-scale LNV effects

- Standard LG works, but requires $m_N \gtrsim 10^9$ GeV  
  Davidson & Ibarra (2002)

- What if we include accessible TeV-scale effects? **Model O2**

Exclusion plot for Model O2  
($m_F = 1$ TeV, $m_S/m_F = 0.5$)

Exclusion plot for Model O2  
($m_F = 1$ TeV, $m_S/m_F = 1.5$)
II. TeV-Scale and Energy frontier probes

Leptogenesis

TeV-scale
LNV

$0\nu\beta\beta$-decay

Collider physics
**LNV searches at colliders**

- **Signal:** two same-sign leptons and two jets, $pp \rightarrow jj\ell^{\pm}\ell^{\pm}$

- **Background:**
  1. SM processes with 2SS leptons (e.g., $jjWW$, $t\bar{t}W$, $t\bar{t}Z$)
  2. Charge misidentification (e.g., $t\bar{t}$, $Z/\gamma^*$)
  3. Jet-fakes (e.g., $t\bar{t}$, $W + 3j$)

* Dominant contributions
TeV-scale LNV effects

- Madgraph + Pythia 8 + Delphes for MC simulation
- Use of Neural Networks for signal/background discrimination

Exclusion plot for Model O2
($m_F = 1$ TeV, $m_S/m_F = 0.5$)

$K = 10^{-2}$

$K = 10^2$

$L = 0.1 \text{ ab}^{-1}$

$L = 3 \text{ ab}^{-1}$

Exclusion plot for Model O2
($m_F = 1$ TeV, $m_S/m_F = 1.5$)

$K = 10^{-2}$

$K = 10^2$

$L = 0.1 \text{ ab}^{-1}$

$L = 3 \text{ ab}^{-1}$
III. TeV-Scale and $0\nu\beta\beta$—decay

Leptogenesis

TeV-scale
LNV

$0\nu\beta\beta$—decay

Collider physics
$\beta -$decays

$2\nu\beta\beta -$decay

Consistent with SM
Very rare but experimentally tested
$\Delta\mathcal{L} = 0$

$0\nu\beta\beta -$decay

Not allowed in SM
Experimentally unseen
$\Delta\mathcal{L} = 2$

Viewpoint: The Hunt for No Neutrinos (Physics 11, 30)
From simplified models to effective operators

1. Obtain the $0\nu\beta\beta$–decay operator after integrating out heavy d.o.f:
   \[ \mathcal{O} \propto \bar{u}u\bar{d}d\bar{e}e \]

2. Match quark-electron operators onto two-nucleon operators

3. Using nuclear physics, calculate the half-life

Physics World (May 09, 2019)
TeV-scale LNV effects

Exclusion plot for Model O2
\( (m_F = 1 \text{ TeV}, m_S/m_F = 0.5) \)

\[ g_Q \]

\[ g_L \]

\[ K = 10^{-2} \]

KamLAND-Zen

Tonne-scale

\[ \mathcal{L} = 0.1 \text{ ab}^{-1} \]

\[ \mathcal{L} = 3 \text{ ab}^{-1} \]

Exclusion plot for Model O2
\( (m_F = 1 \text{ TeV}, m_S/m_F = 1.5) \)

\[ g_Q \]

\[ g_L \]

\[ K = 10^{-2} \]

KamLAND-Zen

Tonne-scale

\[ \mathcal{L} = 0.1 \text{ ab}^{-1} \]

\[ \mathcal{L} = 3 \text{ ab}^{-1} \]
IV. Conclusions

• We have a well-motivated framework to perform different studies

• Rich phenomenology connecting different energy scales:
  A. Nuclear physics
  B. Collider physics
  C. Cosmology

• Complementarity between these different but related scenarios

• Promising options to falsify one of the standard mechanisms to explain the baryon asymmetry
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Backup slides: Dirac and Majorana masses

Dirac mass term: \( m_D \bar{\Psi}\Psi \)

Majorana mass term: \( m_M \bar{\Psi}^c\Psi \)

A Dirac mass has the effect:

\[ \nu \xrightarrow{X} \nu \]

or

\[ \bar{\nu} \xrightarrow{X} \bar{\nu} \]

A Majorana mass has the effect:

\[ \nu \xrightarrow{X} \bar{\nu} \]

or

\[ \bar{\nu} \xrightarrow{X} \nu \]

arXiv:1805.00922
"Candidate isotopes for detecting the $0\nu\beta\beta$ are even-even nuclei that, due to the nuclear pairing force, are lighter than the odd-odd ($A, Z + 1$) nucleus, making single beta decay kinematically forbidden."
Backup slides: Neutrinoless double beta decay

- Two $e^-$ and no $\bar{\nu}_e$ are emitted: $(A, Z) \rightarrow (A, Z + 2) + 2e^- + Q_{\beta\beta}$
- Not allowed in the SM: $\Delta\mathcal{L} \neq 0$
- Experimentally unseen

**Black Box Theorem**

**Majorana mass term**: $\Delta\mathcal{L} = 2$

Backup slides: Effective operators

\[ \pi \pi e e \quad \text{NN} \pi e e \quad \text{NNNN} \pi e e \]

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<th>( O_{2-}^{\pm\pm} )</th>
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Backup slides: Nuclear Matrix Elements

Computing methods:
- EDF: energy-density functional
- QRPA: quasi-particle random phase approximation
- SM: shell model
- IBM: interacting boson model

arXiv: 1902.04097
Backup slides: Lagrangian for Model O2

\[ \mathcal{L}_{O2} = g_Q \overline{Q} S d_R + g_L \overline{L} \tilde{S} F - m_S^2 S^\dagger S - \frac{m_F}{2} F^c F + \text{h.c.} \]

\[ \overline{X} \equiv \epsilon X^*, \quad \epsilon^{12} = +1 \]
Backup slides: Background types

- **Jets from initial/final state radiation** can be misidentified as prompt leptons.

- **Trident event:** $e^-e^+\gamma\rightarrow e^-e^+e^-$
  Electromagnetic cluster can be matched to wrong electron track in ID.

- **Prompt** muon from $W^+$ decay.
  Clean signature, high-$p_T$ and isolated. Leptons from $Z, W, H$ decays estimated with simulation.

- **Non-prompt** lepton from a B-hadron secondary decay, which are associated with hadron activities such as K and n. Less isolated object and larger impact parameter.
Backup slides: Previous study of Model O2

\[ \mathcal{L} = 100 \text{fb}^{-1} \]
\[ \mathcal{L} = 300 \text{fb}^{-1} \]
\[ \mathcal{L} = 3000 \text{fb}^{-1} \]

\[ g_{\text{eff}} \]

\[ \Lambda \text{ (TeV)} \]

GERDA

1 Tonne

arXiv:1508.04444