Baryon number violation via Majorana neutrinos

Yue Zhang

Citation: AIP Conference Proceedings **1743**, 030011 (2016); doi: 10.1063/1.4953292
View online: http://dx.doi.org/10.1063/1.4953292
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1743?ver=pdfcov
Published by the AIP Publishing

Baryon Number Violation via Majorana Neutrinos

Yue Zhang

Walter Burke Institute for Theoretical Physics,
California Institute of Technology, Pasadena, CA 91125

yuezhang@theory.caltech.edu

Abstract. We propose and investigate a novel, minimal, and experimentally testable framework for baryo- genesis, dubbed dexiogenesis, using baryon number violating effective interactions of right-handed Majorana neutrinos responsible for the seesaw mechanism. The distinct LHC signature of our framework is same-sign top quark final states, possibly originating from displaced vertices. The region of parameters relevant for LHC phenomenology can also yield concomitant signals in nucleon decay experiments. We provide a simple ultraviolet origin for our effective operators, by adding a color-triplet scalar, which could ultimately arise from a grand unified theory.

INTRODUCTION

Baryon and lepton numbers are the global symmetries of the standard model (SM) at low temperature. It is commonly believed that global symmetries cannot be exact. Thus it is a natural question to ask and test experimentally to what extent are these conserved quantum numbers.

There are also good reasons to consider models that violates baryon and lepton numbers. The violation of baryon number could be the origin of the cosmic matter-anti-matter asymmetry [1], and lepton number violation might explain the non-zero neutrino masses [2]. Given a theory that achieves either of this, one would then ask what are the other consequences that can be probed experimentally. One of most discussed framework is grand unified theory [5], where both baryon and lepton numbers are spontaneously broken at high very scale, and usually leads to nucleon decays. There are also the partial unification theories like the Pati-Salam model [3] or left-right symmetric model [4], where baryon and/or lepton could be broken at lower (TeV–PeV) scale and leads to phenomena like neutrino-anti-neutron oscillation and lepton number violating processes [6, 7] that may be accessible in present and future laboratories. Models that gauge only $U(1)_B$ and $U(1)_L$ are simpler and have also been studied [8].

In this talk based on [9], we take a different point of view. While the more unified frameworks are nice looking , their structures have to be discovered in order. At any stage, for processes involving light particles that are discovered first, it is convenient to use the effective language by including higher dimensional operators. More generally, without postulating a priori the requirement to unify (which is not known to be the law of nature or not), it is possible to use the effective language to cover more scenarios of B and L violation.

As the starting point, we will consider the type I seesaw mechanism that gives Majorana to the active neutrinos. The Lagrangian is

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2} i\bar{N}_a \gamma \cdot \partial N_a - \frac{1}{2} M_a N_a N_a + y_{ia} \bar{L}_i (i\sigma_2) H^* N_a + \text{h.c.} \,, \tag{1}$$

where N_a are the right-handed neutrinos, $a = 1, 2$, L_i are the SM lepton doublets, $i = 1, 2, 3$. The active neutrino masses are generated after electroweak symmetry breaking, $m_\nu = -v^2 y M^{-1} y^T$. Neutrino oscillation experiments in together with cosmology have set the mass scale of the active neutrinos to be of order $\sim 0.1\,$eV. There are two sets of parameters in the type I seesaw model, one is the right-handed neutrino mass, the other is the neutrino Yukawa coupling. One popular option is to have $y \sim 1$ so that $M \sim O(10^{14})\,$GeV is close to the unification scale. However, such heavy right-handed neutrinos make themselves hard to probe in laboratories today.

We are mostly interested in the case where right-handed neutrino masses lie around the electroweak scale. In this case, the Yukawa coupling typically has to be tiny, $y \sim O(10^{-6})$, in order to make up the correct active neutrino

CETUP 2015 – Workshop on Dark Matter, Neutrino Physics and Astrophysics and PPC 2015 – IXth International Conference on Interconnections between Particle Physics and Cosmology*
AIP Conf. Proc. 1743, 030011-1–030011-6; doi: 10.1063/1.4953292
Published by AIP Publishing. 978-0-7354-1400-6/$30.00

masses. As a result, the mixing between the right-handed and active neutrinos is also of order $\theta_{N\nu} \sim O(10^{-6})$. Probing seesaw mechanism involves probing the Majorana nature of right-handed neutrinos, The small mixing makes the task challenging, simply because the right-handed neutrinos are too weakly coupled to SM particles, so the cross section of producing them is too small. There are several ways out in order to make lepton number violation via right-handed neutrinos accessible in laboratories, especially at colliders. One elegant solution is provided by the left-right symmetric model, where the seesaw mechanism was born. The left-right model contains a new right-handed current interaction for the right-handed neutrinos [6]. If the gauge boson ($W_R^\pm$) associated with this new current interaction has mass of order TeV scale, it could be produced at the Large Hadron Collider (LHC), and the subsequent decay serves as a new production channel of the right-handed neutrinos. Another sometimes discussed scenario is to stick to the type I seesaw setup but fine-tune the neutrino Yukawa couplings to be much larger than 10^{-6} [10, 11]. This helps to boost the production of right-handed neutrinos in the $W^{(*)} \to N\ell$ channel, and is shown to be possible with more than one generation of neutrinos [12, 13]. However, in order to test the seesaw mechanism (the inverse problem), one still has to measure the Yukawa coupling and reach the uncertainty at 10^{-6} level, no matter how large the Yukawa is.

The general lesson we learn from the above considerations is that the TeV right-handed neutrinos for the seesaw mechanism are very weakly coupled to SM particles. In our opinion, this also implies that the physics of right-handed neutrinos is very sensitive to any higher dimensional operators generated by new physics if its scale is sufficiently low.

We will investigate a scenario which is a simple step beyond the type I seesaw model and includes baryon number violating dimension 6 effective operators involving the right-handed neutrinos and SM particles (in additional to those involving SM particle only [14])

$$\delta\mathcal{L}_{\rm BV} = \frac{\lambda_a^{ijk}}{\Lambda^2}[N_a u_i d_j d_k]_R + \frac{\kappa_a^{ilm}}{\Lambda^2}[N_a d_i]_R[Q_l Q_m]_L + \text{h.c.}\,, \tag{2}$$

where i, j, k are family numbers of right-handed quark mass eigenstates and l, m enumerate left-handed quark generations. Here, λ_a^{ijk} and κ_a^{ilm} are generally complex constants determined by the ultraviolet theory. These operators could arise from grand unified theories. They are the lowest dimensional operators that allow RHNs to couple to baryon number directly. We will be interested the cutoff scale not far above a TeV scale so that the new interaction can have an impact on the right-handed neutrino production at the LHC. For a partial list of other works whose subjects have some overlap with that of this letter, see, for example, Refs. [15, 16, 17, 18].

PROTON DECAY

The interaction (2) itself could lead to proton decay if the right-handed neutrinos are lighter than GeV [19]. For heavy right-handed neutrinos, the sum of (1) and (2) can lead to nucleon decay. It is worth noticing that the constraints on $\lambda_a^{ijk}/\Lambda^2$ and κ_a^{ilm}/Λ^2 are flavor dependent. The least constrained operator is the one involving only third generation right-handed quarks,

$$\lambda_a \frac{[\bar{N}_a^c P_R b][\bar{t}^c P_R b]}{\Lambda^2}\,, \tag{3}$$

which originates from the first term in Eq. (2), with explicit spinor contractions. The operators containing left-handed fields are always more constrained because mass diagonalization will inevitably introduce first generation quarks.

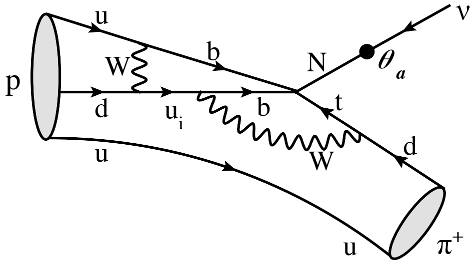

FIGURE 1. One of the leading diagrams that yield proton decay.

Next we study the constraint on the operator Eq. (3) from proton decay. While it does not contain light quarks, quantum loop corrections can induce nucleon decay via these baryon number violating interactions. Fig. 1 provides a sample two-loop diagram that mediates such processes. The corresponding proton decay rate is,

$$\Gamma(p \to \pi^+ \nu) = \frac{(1+g_A)^2 \alpha^2 m_p}{32\pi f_\pi^2} |\xi|^2 \,, \tag{4}$$

where $g_A = 1.27$ is the nucleon axial charge, $f_\pi = 131\,\mathrm{MeV}$ is pion decay constant, and we have used the result of lattice calculations [20] for the form factor $\alpha \approx -0.01125\,\mathrm{GeV}^3$. The factor

$$\xi \approx \frac{\Lambda_{qcd} G_F^2 m_t m_b^2 V_{td}^2 V_{ub}^* V_{tb}^*}{(16\pi^2)^2 \Lambda^2} \lambda_a \theta_a \,, \tag{5}$$

is the Wilson coefficient from estimating the two-loop diagram in Fig. 1. The angle θ_a is the mixing between N_a and the SM active neutrinos. The hadronic mass scale $\Lambda_{qcd} \approx 200\,\mathrm{MeV}$ must be introduced under a symmetry argument. The operator we started with is $[\bar{N}_a^c P_R b][\bar{t}^c P_R b]$, and after the W-loop dressing as in Fig. 1, the operator for proton decay turns out to be $[\bar{N}_a^c P_R d][\bar{u}^c P_L d]$ (which is the radiatively generated $NdQQ$ operator mentioned earlier). The fact that one of the downs quark is still right-handed implies an external (constituent) quark mass insertion, $\sim \Lambda_{qcd}$.

The resulting proton decay life time is

$$\tau(p \to \pi^+ \nu) \approx 2.5 \times 10^{32}\,\mathrm{yr} \left(\frac{\Lambda/\sqrt{\lambda_a}}{1.5\,\mathrm{TeV}}\right)^4 \left(\frac{\theta_a}{10^{-6}}\right)^{-2} \,. \tag{6}$$

The current experimental lower limit on the $p \to \pi^+ \nu$ decay channel is 1.6×10^{31} yr [21]. Hence, the above lifetime (6) is not far from the current limit and, in the region of parameters considered in our work, can be within the reach of future nucleon decay experiments [22, 23].

DEXIOGENESIS

We notice that the baryon number violating interaction of right-handed neutrinos allow for direct generation of a baryon number asymmetry through RHN decays in the early Universe, which we dub *dexiogenesis* (dexios: Greek for the right hand). This is in contrast to canonical leptogenesis [24] where the lepton asymmetry needs to be further processed into baryon number through electroweak sphalerons [25]. All the necessary ingredients encoded in Sakharov's conditions [1] can be satisfied here for baryogenesis: *(i)* these interactions are manifestly baryon number violating, *(ii)* their complex coefficients provide a source of CP violation, and *(iii)* if the Universe has a low reheat temperature $T_{\mathrm{RH}} \ll M_a$, then the N_a will decay out of equilibrium. This mechanism, dexiogenesis, allows $T_{\mathrm{RH}} \ll 100$ GeV, since the baryon asymmetry is directly generated and hence electroweak sphalerons do not need to be active footnoteThe coupling between a new fermion X and the *udd* operator has been discussed in several dark matter models [19, 30, 31].. Let N_1 be the lighter of the two RHNs in our setup. Then, the interference of the tree and the 2-loop diagrams in Fig. 2 will lead to a baryon asymmetry

$$\epsilon \equiv \frac{\Gamma(N_1 \to tbb) - \Gamma(N_1 \to \bar{t}\bar{b}\bar{b})}{2\Gamma_{N_1}} \,, \tag{7}$$

where the width of N_1 is given by $\Gamma_{N_1} = \frac{|\lambda_1|^2 M_1^5}{1024\pi^3\Lambda^4} F\left(m_t^2/M_1^2\right)$, with $F(x) = 1 - 8x - 12x^2 \log x + 8x^3 - x^4$.

In the presence of the higher dimensional operator Eq. (3) with a TeV scale cutoff, N_1 decay induced by neutrino Yukawa interactions is subdominant, for values of M_1 near the weak scale. Given a realistic seesaw mechanism for the SM active neutrino masses, in general we have $y_N^a \lesssim 10^{-6}\sqrt{M_1/(200\,\mathrm{GeV})}$ in the absence of fine tuning [32]. The induced $N_1 \to W\ell$ decay rate is then estimated to be $\Gamma_{N_1 \to W\ell} \lesssim 10^{-12}\,\mathrm{GeV}\,(y_N^a/10^{-6})^2\,[M_1/(200\,\mathrm{GeV})]$. We find that, for M_1 of a few hundred GeV and $\Lambda/\sqrt{\lambda_1} \lesssim 50\,\mathrm{TeV}$, that rate is smaller than the baryonic decay rate.

The baryon asymmetry can be conveniently obtained using the unitarity cut method [33]

$$\epsilon = \frac{\mathrm{Im}(\lambda_1^2 \lambda_2^{*2})}{3072\pi^3 |\lambda_1|^2} \left(\frac{M_1}{\Lambda}\right)^4 \frac{M_1 M_2}{(M_2^2 - M_1^2)} \,. \tag{8}$$

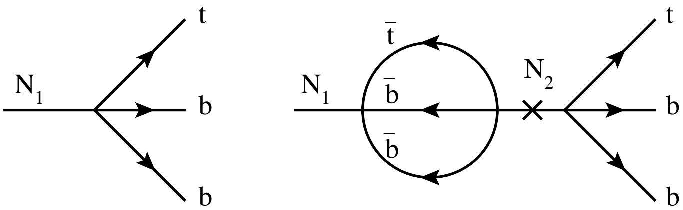

FIGURE 2. Tree and two-loop diagrams for dexiogenesis.

The relation between the above asymmetry and the baryon number to entropy ratio $\eta \equiv n_B/s \sim 10^{-10}$ [21] depends on the non-thermal production mechanism for N_1, but it can plausibly be $\eta \sim \epsilon/100$. For example, let us assume that a heavy modulus, such as an inflaton, decays equally into radiation and N_1, which promptly decays. We will take the reheat temperature to be $T_{\rm RH} \sim 1$ GeV. Then, one can estimate $\eta \sim \epsilon/g^*$ where $g^* \sim 100$ is the number of relativistic degrees of freedom at $T_{\rm RH}$. Alternatively, if the modulus decays exclusively into N_1, and it is the decay of N_1 that reheats the Universe, we end up with $\eta \sim \epsilon\, T_{\rm RH}/M_1$, which for $M_1 \sim 100$ GeV, again yields $\eta \sim \epsilon/100$. Hence, for $M_1 \sim M_2$ and $\lambda_a \sim 1$, we typically require $M_1/\Lambda \gtrsim 0.1$. Consequently, for $M_1 \lesssim 1$ TeV, relevant for collider phenomenology, the cutoff scale must be sufficiently low, $\Lambda \lesssim 10$ TeV. Let us then examine the experimental constraints on Λ.

COLLIDER SIGNATURES

An immediate consequence of Eq. (3) is the possible production of same-sign top quarks at the LHC and future hadron colliders, due to the Majorana nature of RHNs (see the left panel of Fig. 3). In this process, the RHN N_a and a top quark are first produced, and then N_a decays into another top quark and two bottom quarks. Because it is a Majorana particle, an on-shell N_a is equally likely to decay into tbb or $\bar{t}\bar{b}\bar{b}$ final states. The violation of baryon number is manifested in terms of the violation of top quark number (by two units). The sign of the top quark can be inferred from its leptonic decay. For a RHN with a few hundred GeV mass and the effective cutoff scale $\Lambda/\sqrt{\lambda_a}$ of a few TeV, we find that the cross section for this process can be as large as ~ 0.3 fb in the LHC Run-II at 13 TeV. The main background for this signal is from $t\bar{t}b\bar{b}$ final states with the lepton charge from a top quark decay misidentified, which is suppressed by the small misidentification rate [34]. In Table 1, we list the leading order cross sections of our signal for several sample mass values of RHNs. These points have not been excluded by the existing LHC data. For example, with $M_a = 200$ GeV and $\Lambda/\sqrt{\lambda_a} = 1.5$ TeV, the cross section at 8 TeV is 0.07 fb, which implies only 1-2 events given the existing integrated luminosity $\sim 27\,{\rm fb}^{-1}$, and is further suppressed by top quark leptonic branching ratio.

TABLE 1. Same-sign top quark production cross section, at the 13 TeV LHC, via a Majorana RHN and the contact operators in Eq. (3). The cutoff scale is fixed to be $\Lambda/\sqrt{\lambda_a} = 1.5$ TeV.

$\sigma(pp \to tN \to ttbb)$				
M_a	200 GeV	500 GeV	800 GeV	1 TeV
$\sqrt{s} = 13$ TeV	0.34 fb	0.16 fb	8×10^{-2} fb	5×10^{-2} fb

Following the same logic as introducing RHNs to make the SM renormalizable, we now discuss a UV completion that generates the effective operator Eq. (3). Given a TeV scale cutoff, it is possible to directly probe the heavy particles in such a model in LHC Run-II and future hadron colliders. The model is an extension of the SM that contains a color-triplet scalar, T, with quantum numbers $(\bar{3}, 1, 1/3)$. The corresponding Lagrangian is

$$\mathcal{L}_{\rm UV} = f_a\, T\, \bar{N}_a^c P_R b + f'\, T^*\, \bar{t}^c P_R b + M_T^2 |T|^2 \,. \tag{9}$$

In fact, this is the simplest model that yields the flavor and color structures of the effective operators in Eq. (3), after integrating out the color-triplet scalar T, corresponding to a cutoff $\lambda_a/\Lambda^2 \equiv f_a f'/M_T^2$. The TeV scale cutoff as discussed above can be naturally obtained for $M_T \sim$ TeV and $f_a f' \sim \mathcal{O}(1)$. We note that in the above UV model, it is

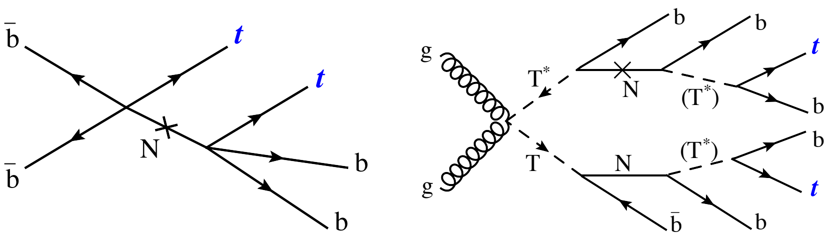

FIGURE 3. Feynman diagrams for same-sign top quark events that can happen at hadron colliders, using the Majorana nature of RHNs and the baryonic interactions of Eq. (3). **Left**: $pp \to tN$ production via the contact operator Eq. (3), followed by the decay $N \to tbb$. **Right**: process in the UV complete model, pair production of color-triplet scalars T, T^*, and followed by $T \to N\bar{b}$, $T^* \to Nb$, and $N \to tbb$ (via virtual T in parentheses). Baryon number and top quark number are broken when both RHNs decay into top quarks using a Majorana mass insertion.

possible to have baryogenesis through the decays of the T particle [28]. We will not further explore such a possibility in this work. The introduction of the scalar T could offer richer phenomenology at colliders. If light enough, T, T^* can be pair produced at hadron colliders. Each triplet will first decay into $N + b$, which is then followed by subsequent decay $N \to t\,b\,b$ via a virtual T. The above chain of processes are represented by the diagram in the right panel of Fig. 3. These together result in same-sign top quark final states with many b-jets. In Table 2, we give the leading-order QCD cross section for the T, T^* pair production at the 13 TeV LHC and a 100 TeV proton-proton collider, calculated with MadGraph [35].

TABLE 2. Pair production cross sections of T, T^* via strong interaction at the 13 and 100 TeV proton-proton colliders.

$\sigma(pp \to TT^*)$				
M_T	1.5 TeV	2 TeV	5 TeV	10 TeV
$\sqrt{s} = 13$ TeV	0.16 fb	0.01 fb	—	—
$\sqrt{s} = 100$ TeV	384 fb	92 fb	0.54 fb	4×10^{-3} fb

Moreover, an additional distinct signal could be displaced vertices from the decay of RHNs, if we take a somewhat larger cutoff scale $\Lambda/\sqrt{\lambda_a}$. In fact, we find for $M_1 = 200$ GeV and $\Lambda/\sqrt{\lambda_1} \gtrsim 7$ TeV, the decay of N is displaced, $c\tau_{N_1} \gtrsim 100\,\mu$m, which would be detectable at the LHC [36]. This could result from Eq. (9) for $M_T \sim 1-2$ TeV and $f_a \sim f' \sim 0.2$. Events with same-sign tops and displaced vertices would be quite striking and hard to miss in collider experiments. Meanwhile, if the corresponding neutrino Yukawa coupling of N_1 is $y_N^1 \gtrsim 10^{-7}$, sufficient to explain the solar neutrino mass difference [21], the partial decay rate of $N_1 \to W\ell$ can be as large as order one. The leptonic decays can be used to identify N_1 as a RH neutrino (see, *e.g.*, [37]).

CONCLUSION

To summarize, we studied a simple extension of the type I seesaw mechanism by including baryon number violating right-handed neutrino interactions in terms of higher dimensional operators. We find that for one type of operators that involve third generation right-handed quarks, the proton decay only constrains the effective cutoff scale up to a few TeV scale. This offers us a new opportunity of generating the cosmic baryon asymmetry using the baryonic decay of the right-handed neutrinos. At the same time, the same operator also leads to exciting collider signature in the same sign top quarks channel, the violation of baryon number (by two units) is manifested in the violation of top quark number. This piece of new physics makes connection among early universe, high-energy and deep underground nucleon decay experiments.

ACKNOWLEDGMENTS

I thank the organizers (K.S. Babu and Barbara Szczerbinska) for the invitation to the CETUP* 2015 workshop.

REFERENCES

[1] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5**, 32 (1967) [JETP Lett. **5**, 24 (1967)] [Sov. Phys. Usp. **34**, 392 (1991)] [Usp. Fiz. Nauk **161**, 61 (1991)].

[2] P. Minkowski, Phys. Lett. B **67** (1977) 421. R. Mohapatra, G. Senjanović, Phys. Rev. Lett. **44** (1980) 912. T. Yanagida, *Workshop on unified theories and baryon number in the universe*, ed. A. Sawada, A. Sugamoto (KEK, Tsukuba, 1979). S. Glashow, *Quarks and leptons, Cargèse 1979*, ed. M. Lévy (Plenum, NY, 1980). M. Gell-Mann, P. Ramond, R. Slansky, *Supergravity Stony Brook workshop, New York, 1979*, ed. P. Van Niewenhuizen, D. Freeman (North Holland, Amsterdam, 1980).

[3] J. C. Pati and A. Salam, Phys. Rev. D **8**, 1240 (1973).

[4] R. N. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 566 (1975). G. Senjanovic and R. N. Mohapatra, Phys. Rev. D **12**, 1502 (1975). R. Mohapatra, G. Senjanović, Phys. Rev. Lett. **44** (1980) 912.

[5] H. Georgi and S. L. Glashow, Phys. Rev. Lett. **32**, 438 (1974).

[6] W. Y. Keung and G. Senjanovic, Phys. Rev. Lett. **50**, 1427 (1983).

[7] M. Nemevsek, F. Nesti, G. Senjanovic and Y. Zhang, Phys. Rev. D **83**, 115014 (2011) [arXiv:1103.1627 [hep-ph]]. V. Tello, M. Nemevsek, F. Nesti, G. Senjanovic and F. Vissani, Phys. Rev. Lett. **106**, 151801 (2011) [arXiv:1011.3522 [hep-ph]].

[8] P. Fileviez Perez and M. B. Wise, Phys. Rev. D **82**, 011901 (2010) [Phys. Rev. D **82**, 079901 (2010)] [arXiv:1002.1754 [hep-ph]].

[9] H. Davoudiasl and Y. Zhang, Phys. Rev. D **92**, no. 1, 016005 (2015) [arXiv:1504.07244 [hep-ph]].

[10] A. Datta, M. Guchait and A. Pilaftsis, Phys. Rev. D **50**, 3195 (1994) [hep-ph/9311257].

[11] A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP **0905**, 030 (2009) [arXiv:0901.3589 [hep-ph]].

[12] A. Ibarra and G. G. Ross, Phys. Lett. B **591**, 285 (2004) [hep-ph/0312138].

[13] J. Kersten and A. Y. Smirnov, Phys. Rev. D **76**, 073005 (2007) [arXiv:0705.3221 [hep-ph]].

[14] S. Weinberg, Phys. Rev. Lett. **43**, 1566 (1979).

[15] C. Cheung and K. Ishiwata, Phys. Rev. D **88**, no. 1, 017901 (2013) [arXiv:1304.0468 [hep-ph]].

[16] D. Aristizabal Sierra, C. S. Fong, E. Nardi and E. Peinado, JCAP **1402**, 013 (2014) [arXiv:1309.4770 [hep-ph]].

[17] I. Baldes, N. F. Bell, A. Millar, K. Petraki and R. R. Volkas, JCAP **1411**, no. 11, 041 (2014) [arXiv:1410.0108 [hep-ph]].

[18] A. Monteux and C. S. Shin, arXiv:1412.5586 [hep-ph].

[19] H. Davoudiasl, Phys. Rev. Lett. **114**, no. 5, 051802 (2015) [arXiv:1409.4823 [hep-ph]].

[20] Y. Aoki *et al.* [RBC-UKQCD Collaboration], Phys. Rev. D **78**, 054505 (2008) [arXiv:0806.1031 [hep-lat]]. Y. Aoki, C. Dawson, J. Noaki and A. Soni, Phys. Rev. D **75**, 014507 (2007) [hep-lat/0607002].

[21] K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38**, 090001 (2014).

[22] Y. Suzuki *et al.* [TITAND Working Group Collaboration], hep-ex/0110005; M. V. Diwan, R. L. Hahn, W. Marciano, B. Viren, R. Svoboda, W. Frati, K. Lande and A. K. Mann *et al.*, hep-ex/0306053; A. Bueno, Z. Dai, Y. Ge, M. Laffranchi, A. J. Melgarejo, A. Meregaglia, S. Navas and A. Rubbia, JHEP **0704**, 041 (2007) [hep-ph/0701101].

[23] K. S. Babu, E. Kearns, U. Al-Binni, S. Banerjee, D. V. Baxter, Z. Berezhiani, M. Bergevin and S. Bhattacharya *et al.*, arXiv:1311.5285 [hep-ph].

[24] M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986).

[25] For earlier attempts on baryogenesis without sphalerons, see *e.g.*, Refs. [26, 27, 28, 29].

[26] S. Dimopoulos and L. J. Hall, Phys. Lett. B **196**, 135 (1987).

[27] K. S. Babu, R. N. Mohapatra and S. Nasri, Phys. Rev. Lett. **97**, 131301 (2006) [hep-ph/0606144].

[28] H. An and Y. Zhang, Phys. Rev. D **89**, no. 7, 071902 (2014) [arXiv:1310.2608 [hep-ph]].

[29] Y. Cui and R. Sundrum, Phys. Rev. D **87**, no. 11, 116013 (2013) [arXiv:1212.2973 [hep-ph]].

[30] H. Davoudiasl, D. E. Morrissey, K. Sigurdson and S. Tulin, Phys. Rev. Lett. **105**, 211304 (2010) [arXiv:1008.2399 [hep-ph]].

[31] J. Shelton and K. M. Zurek, Phys. Rev. D **82**, 123512 (2010) [arXiv:1008.1997 [hep-ph]].

[32] We will not consider the very fine-tuned case of large neutrino Yukawa couplings, which could yield mixings between RHNs and active neutrinos $\gg 10^{-6}$ [10, 11].

[33] M. D. Schwartz, "Quantum Field Theory and the Standard Model," ISBN-9781107034730.

[34] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1104**, 050 (2011) [arXiv:1103.3470 [hep-ex]].

[35] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, JHEP **1106**, 128 (2011) [arXiv:1106.0522 [hep-ph]].

[36] T. Han, hep-ph/0508097.

[37] M. Nemevsek, G. Senjanovic and V. Tello, Phys. Rev. Lett. **110**, no. 15, 151802 (2013) [arXiv:1211.2837 [hep-ph]].