Can colliders disprove leptogenesis?

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Summary. — While leptogenesis is a very solid but hard to check contender for the generation of the observed excess of baryons over anti-baryons in the Universe, we show that the observation of gauge bosons associated with right-handed currents at present or future colliders would suffice to disprove its most canonical mechanism.

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PACS `11.30.Fs` – Global symmetries (e.g., baryon number, lepton number).,
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1. – Introduction

This short article will outline a suggestion, not really for testing leptogenesis in general terms, but rather to disprove it, should some gauge bosons coupled to the right-handed fermions (we will call them generically "Right-Handed W's" or W_R) be discovered at current or future colliders.

We begin by a quick recapitulation of the leptogenesis scheme, insisting on its attractiveness, its robustness, but also on the difficulty to submit it to experimental verification. We will later insist on the fact that extended gauge symmetries are the natural framework for leptogenesis, and show that the discovery of right-handed W's would infirm the "canonical" leptogenesis mechanism.

Full details of this latter analysis can be found in our common work with Thomas Hambye and Gilles Vertongen [1], where a more complete bibliography is also provided.

2. – Why leptogenesis?

The current excess of baryons (in fact we don't know about matter in general, since we can't count the cosmic background neutrinos) over anti-baryons is one of the big observational evidences calling for explanation. A first suggestion came from Grand Unified theories, more specifically SU(5), but quickly met with an objection related to the late evolution of the Universe. Anomalies and the resultant non-conservation of B and L, when operative at the electroweak transition could indeed destroy a previously generated baryon asymmetry on the simple condition that it be consistent with $B-L=0$, which is precisely the case in SU(5).

The obvious answers are to use this late occasion either as a new source of B generation (electroweak baryogenesis), or as a way to mutate a previously generated asymmetry into the observed B number: in this latter case, it is necessary that the previous asymmetry satisfy $B - L \neq 0$.

As is now well-known, the first possibility, despite its elegance, fails in the Standard Model alone, for lack both of sufficient CP violation, and of the out-of-equilibrium component which requires a first order phase transition. This can be fixed in more extended models (additional singlets, supersymmetry), but the scheme keeps requiring new CP violation, and depends very heavily on the poorly controlled dynamics of the B and L violation at the phase transition.

The choice solution therefore has become leptogenesis [2]. In its canonical form, it is closely associated to the see-saw mechanism, where heavy right-handed neutrinos coupled by Yukawas to the left-handed ones, are used to generate the very small observed masses. The large Majorana mass of the neutrinos provides the necessary L violation, the small Yukawa couplings provide the out-of-equilibrium decays, in such a way that a very robust L asymmetry is generated at high temperature. At the electroweak phase transition, a fraction of this L is converted into a baryonic asymmetry. One of the big advantages is that this conversion process operates by reaching some equilibrium between B and L components, and is fairly independent on the precise dynamics of the B violation at the (slow) electroweak phase transition.

The difficulty to prove leptogenesis resides precisely in its sturdiness, and its quite generic character. Even if the main elements appearing in the calculation of the leptonic (and later baryonic) asymmetry are the same as those governing the (accessible) light neutrino masses, they intervene in completely different combinations, so that low energy data are not constraining for the process.

In this note, we will show that, even if leptogenesis is difficult to establish, and fairly resilient as a mechanism, it could still be excluded if W_R particles are observed at colliders.

3. – Orders of Magnitude

Let us take as a starting point the mass terms for the heavy right-handed neutrinos N, and their Yukawa couplings to the light ones, namely:

$$\mathcal{L}_{mass} = -\overline{L}\,\widetilde{H}\,\lambda_\nu^\dagger\,N - \frac{1}{2}\,\overline{N}\,m_N\,N^c + \text{h.c.} \tag{1}$$

where λ is a matrix in generation space, H is the Brout-Englert-Higgs doublet (possibly part of a larger grand-unified multiplet) , L are the light left-handed fermions.

Since we are just interested here in orders of magnitude, we will use in this paragraph λ as a single number, assuming (wrongly) that all Yukawa couplings are of similar size. We want now to express the conditions (the values of λ) that provide the correct order of magnitude for light neutrino masses, for the out-of-equilibrium decay of the heavy N, and for sufficient CP violation.

CP violation is provided by the interference of tree-level and one loop diagrams, all controlled by λ. Unless there is a special enhancement, we may thus expect the amount of CP violation to be of order λ^4, while the direct decays are of order λ^2. The proportion of CP violating decay for each heavy N is thus expected to be of order λ^2 (see Fig 1).

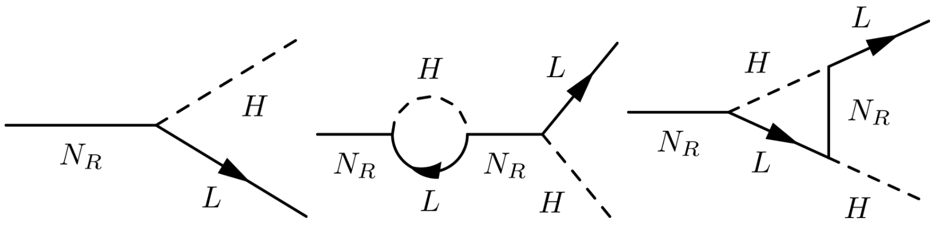

Fig. 1. – N Decay and CP violation

Since other effects tend to dilute the baryogenesis effect, this amount of CP asymmetry must exceed the wanted early universe asymmetry, namely $\epsilon > 10^{-8}$

The out-of-equilibrium condition states that the decay rate must be slower than the Universe expansion at the time of decoupling (that is, roughly at temperature $T \approx m_N$). Here g^* is the effective number of degrees of freedom at that time.

$$\begin{aligned} \Gamma &\simeq \lambda^2 m \\ \Gamma &\ll H \\ H &= \sqrt{g^*}T^2/(10^{19}GeV) \end{aligned} \tag{2}$$

We group in Table I the various constraints on λ and m_N, adding the request to get reasonable light neutrino masses (say, of order $0.01eV$, through the see-saw formula $m_\nu = \lambda^2 v2/M$, where $v \approx 100GeV$ is the electroweak symmetry breaking.

As seen clearly from this table, the leptogenesis mechanism is fairly resilient over a wide range of λ, m_N, but tuning becomes needed for low values of these parameters. Such tuning can take place either through adjusting the individual elements of the Yukawa coupling matrix λ, or a considerable enhancement can be found by making the self-energy diagram nearly resonant. This is obviously another kind of tuning, which requests the heavy neutrinos $N_1, N_2, ..$ to be nearly degenerate. If the mass splitting is of order λ^2, the CP violation asymmetry can then be considerable. Arguably, very low energy leptogenesis could then take place [3].

Table I. – *Bounds on m_N (in GeV) for various λ , assuming a light neutrino mass of order .01 eV*

λ	Light neutrino mass $m_N \sim (GeV)$	Out of Equilibrium decay $m_N > (GeV)$	enough CP violation
10^{-5}	10^7	10^8	needs tuning
10^{-4}	10^9	10^{10}	bordeline
10^{-3}	10^{11}	10^{12}	yes
10^{-2}	10^{13}	10^{14}	yes
10^{-1}	10^{15}	10^{16}	yes
1	10^{17}	10^{18}	yes

4. – Improving or Falsifying Leptogenesis

As announced, the main point of this note is to stress that, even if it is extremely difficult to establish leptogenesis, it could at least be falsified. In particular, we contend that the observation at present or future colliders (that is in practice in the TeV range) of W_R's would make the canonical form of leptogenesis (the case outlined above, with the lepton number carried by neutrinos) untenable.

The possible observation of a W_R will of course be justification enough for its consideration! Still, a few words of motivation for such a particle may be useful, and may help put back in context the whole leptogenesis approach.

In my view indeed, introducing singlet fermions like the $N's$ of ad-hoc mass (quite separate from the electroweak and grand unification scales) and Yukawa couplings, if done outside a broader context, is mainly a reparametrization of an effective Lagrangian, and involves no less fine tuning than putting by hand the small parameters this construction replaces. The situation is entirely different if such new particles are related to a wider (for instance, gauge) structure, in which case a much more compelling picture emerges.

Without being specific about the wider gauge structure (one may think of SO(10), E6, or broader schemes), some generators and their associated gauge bosons will typically involve $l_R - \nu_R$ (or in the present notation $l_R - N$) transitions. They will also presumably couple to the right-handed quark structure. For this reason, we consider specifically the case of W_R. Other effects may be associated with the other members of the extended structure, notably extra $Z's$, or scalars, but we expect (at least in the case of canonical leptogenesis considered here) that they will usually play in the same direction.

Including the W_R sector was of course already considered, notably in [4] and [5]. In both cases, the study was involved with very heavy extra gauge bosons, and the way they would affect leptogenesis and low-energy implications. The most obvious result, as shown in [4] is that the presence of W_R will introduce new, CP-conserving decay channels, potentially large, and lead to an extra dilution of the generated lepton asymmetry, up to the point that the case $M_{W_R} < m_N$ is virtually excluded. This is however by far not the only effect. Further reduction of leptogenesis is associated to diffusion processes, but quite interestingly , the opposite effect may also arise.

As shown indeed in [5], the presence of W_R may play a determinant role when the N population has been destroyed through inflation and needs to be rebuilt. If, as sometimes assumed, the N don't couple directly to the reheating process, small Yukawa couplings (associated to particularly light neutrinos) would in fact preclude the rebuilding of a sufficient population. In that case, the presence of right-handed gauge interactions saves the day, and destroys the possible lower limits on neutrino masses which could be induced.

5. – The main effects

We start thus by including the new interaction term

$$\mathcal{L}_{W_R} = \frac{g}{\sqrt{2}} W_R^\mu \left(\bar{u}_R \gamma_\mu d_R + \bar{N} \gamma_\mu \, l_R \right) \tag{3}$$

The most evident effect is on the decay channels. Since these are CP-conserving, they introduce a dilution of the asymmetry $\epsilon^{(0)}$ generated in the standard case:

(4) $$\epsilon = \frac{\Gamma_N^{(l)} - \overline{\Gamma}_N^{(l)}}{\Gamma_{tot}^{(l)} + \Gamma_{tot}^{(W_R)}} \equiv \epsilon^{(0)} \frac{\Gamma_{tot}^{(l)}}{\Gamma_{tot}^{(l)} + \Gamma_{tot}^{(W_R)}}$$

We denote the abundances $Y_i \equiv n_i/s$, $Y_\mathcal{B} \equiv Y_B - Y_{\bar{B}}$, $Y_\mathcal{L} \equiv Y_L - Y_{\bar{L}}$, where n_i the comoving number density of the species "i", "eq" refering to the equilibrium number density, and s the comoving entropy density. In a now standard notation,

(5) $$Y_\mathcal{B} = Y_\mathcal{L}\, r_{\mathcal{L}\to\mathcal{B}} = \varepsilon_N\, \eta\, Y_N^{eq}(T \gg m_N)\, r_{\mathcal{L}\to\mathcal{B}}.$$

where $r_{\mathcal{L}\to\mathcal{B}}$ is the conversion rate of lepton to baryon number at the electroweak phase transition, and η is referred to as the efficiency, and involves all the effects of evolution of the lepton number under the Boltzmann equations.

To facilitate the discussion, we will now slightly depart from the usual conventions, and will include the above-mentioned dilution effect (that is , the factor $\frac{\Gamma_{tot}^{(l)}}{\Gamma_{tot}^{(l)}+\Gamma_{tot}^{(W_R)}}$ appearting in eq. 4) in the expression of the efficiency η. Using this convention, $\epsilon \to \epsilon^0$.

We now set to examine if the dilutions effects due to a light W_R are sufficient to make canonical leptogenesis impossible. For this purpose, we can, in the above convention, replace ϵ by the largest possible value. While both degenerate and non-degenerate cases are considered in [1], we will consider here the least favorable situation (for our purpose of disproving the mechanism), namely $\epsilon = 1$ (thus allowing for resonance enhancement).

A very important effect arises from the scatterings. Indeed, the W_R have the important property of interacting with gauge strength with the right-handed quarks in the thermal plasma. This keeps them in thermal equilibrium, but also enhances the effect of the scatterings, since the "relic" N particles interact through W_R with normally abundant quarks and light leptons (at the difference of the case where the relic particles must annihilate mutually).

The results are most easily read from Fig. 2, were we give (in the right-most panel), the lower bound on M_{W_R} compatible with leptogenesis. The values, given in GeV are clearly out of reach of the currently operating or planned colliders (we find a lower bound of 18 TeV in the present case). As an example, we also list (in the left-most panel) the actual efficiencies (which would also be the lepton number generated, in case $\epsilon = 1$) for $M_{W_R} = 3\ TeV$, a value reachable at the LHC. (remember that a leptonic excess of at least 10^{-8} must be generated to accomodate the currently observed matter asymmetry.

The above considerations put some new urgency to the quest at colliders for W_R bosons, or possibly even light N. In particular, the search [6] should be extended to include the situation where the N is heavier than the W_R, a case where the exclusion of leptogenesis is even more severe.

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REFERENCES

[1] J. M. Frere, T. Hambye and G. Vertongen, JHEP **0901**, 051 (2009)

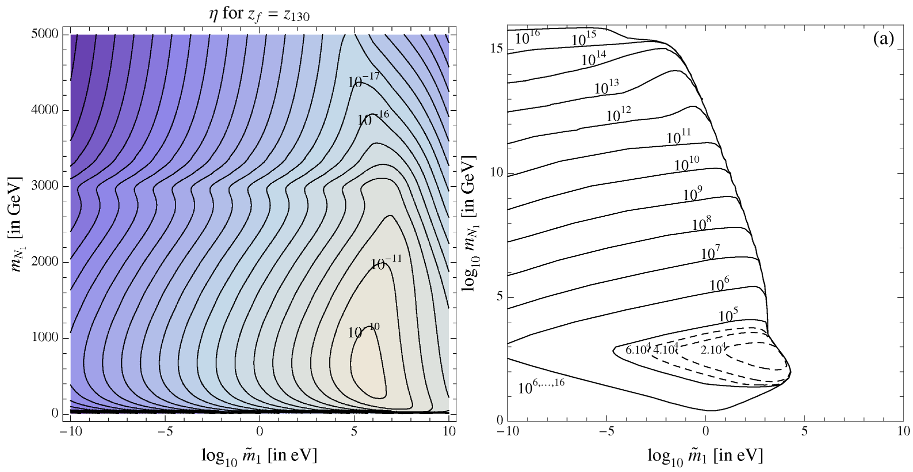

Fig. 2. – Main results: the panel at the left gives for $M_{W_R} = 3TeV$ the efficiencies reached as a function of m_N and $\tilde{m}_1 = v^2 \lambda_\nu^\dagger \lambda_{\nu 11}/m_N$, $(z - f$ refers to the scale at which the decoupling of the sphaleron conversion mechanism is assumed). The panel at the right gives the lower limit acceptable for the W_R mass (in GeV) assuming a maximal leptonic asymmetry due to CP violation $(\epsilon = 1)$

- [2] Fukugita, Yanagida, Phys. Lett. **B174** (1986) 45; for recent reviews see e.g. A. Strumia ; S. Davidson, E. Nardi and Y. Nir, arXiv:0802.2962 [hep-ph];
- [3] L. Covi, E. Roulet and F. Vissani, Phys. Lett. B **384** (1996) 169, A. Pilaftsis, Phys. Rev. D **56** (1997) 5431, M. Flanz, E. A. Paschos and U. Sarkar, Phys. Lett. B **345**, 248 (1995) [Erratum-ibid. B **382**, 447 (1996)]
- [4] S. Carlier, J. M. Frere and F. S. Ling, Phys. Rev. D **60** (1999) 096003 [arXiv:hep-ph/9903300]; E. Ma, S. Sarkar and U. Sarkar, Phys. Lett. **B458** (1999) 73.
- [5] N. Cosme, JHEP **0408** (2004) 027 [arXiv:hep-ph/0403209].
- [6] G. L. Bayatian *et al.* [CMS Collaboration], "CMS physics: Technical design report," CERN/LHCC 2006-021
  V. Buescher, M. S. Carena, B. A. Dobrescu, S. Mrenna, D. Rainwater and M. Schmitt, arXiv:hep-ph/0608322.