RECENT ISSUES IN LEPTOGENESIS

ENRICO NARDI
INFN, Laboratori Nazionali di Frascati, C.P. 13, 100044 Frascati, Italy, and
Instituto de Física, Universidad de Antioquia, A.A.1226, Medellín, Colombia

Baryogenesis via leptogenesis provides an appealing mechanism to explain the observed baryon asymmetry of the Universe. Recent refinements in the understanding of the dynamics of leptogenesis include detailed studies of the effects of lepton flavors and of the role possibly played by the lepton asymmetries generated in the decays of the heavier singlet neutrinos $N_{2,3}$. A review of these recent developments in the theory of leptogenesis is presented.

1 Introduction

The possibility that the Baryon Asymmetry of the Universe (BAU) could originate from a lepton number asymmetry generated in the CP violating decays of the heavy seesaw Majorana neutrinos was put forth about twenty years ago by Fukugita and Yanagida. [1] Their proposal came shortly after Kuzmin, Rubakov and Shaposhnikov pointed out that above the electroweak phase transition $B+L$ is violated by fast electroweak anomalous interactions. [2] This implies that any lepton asymmetry generated in the unbroken phase would be unavoidably converted in part into a baryon asymmetry. However, the discovery that at $T \gtrsim 100\,\text{GeV}$ electroweak interactions do not conserve baryon number, also suggested the exciting possibility that baryogenesis could be a purely standard model (SM) phenomenon, and opened the way to electroweak baryogenesis. [3] Even if rather soon it became clear that within the SM electroweak baryogenesis fails to reproduce the correct BAU by many orders of magnitude, [4] within the minimal supersymmetric standard model (MSSM) the chances of success were much better, and this triggered an intense research activity in that direction. Indeed, in the early 90's electroweak baryogenesis attracted more interest than leptogenesis, but still a few remarkable papers appeared that put the first basis for *quantitative* studies of leptogenesis. Here I will just mention two important contributions that established the structure of the two main ingredients of leptogenesis: the rates for several washout processes relevant for the leptogenesis Boltzmann equations, that were presented by

Luty in his 1992 paper, [5] and the correct expression for the CP violating asymmetry in the decays of the lightest Majorana neutrino, first given in the 1996 paper of Covi, Roulet and Vissani. [6]

Around year 2000 a flourishing of detailed studies of leptogenesis begins, with a corresponding burst in the number of papers dealing with this subject.[7] This raise of interest in leptogenesis can be traced back to two main reasons: firstly, the experimental confirmation (from oscillation experiments) that neutrinos have nonvanishing masses strengthened the case for the seesaw mechanism, that in turn implies the existence, at some large energy scale, of lepton number violating ($\not{L}$) interactions. Secondly, the fact that the various analysis of supersymmetric electroweak baryogenesis cornered this possibility in a quite restricted region of parameter space, leaving for example for the Higgs mass just a 5 GeV window (115 - 120 GeV). [8]

The number of important papers and the list of people that contributed to the development of leptogenesis studies and to understand the various implications for the low energy neutrino parameters is too large to be recalled here. However, let me mention the remarkable paper of Giudice *et al.* [9] that appeared at the end of 2003: in this paper a whole set of thermal corrections for the relevant leptogenesis processes were carefully computed, a couple of mistakes common to previous studies were pointed out and corrected, and a detailed numerical analysis was presented both for the SM and the MSSM cases. Eventually, it was claimed that the residual numerical uncertainties would probably not exceed the 10%-20% level. A couple of years later, Nir, Roulet, Racker and myself [10] carried out a detailed study of additional effects that were not accounted for in the analysis of ref.. [9] This included electroweak and QCD sphaleron effects, the effects of the asymmetry in the Higgs number density, as well as the constraints on the particles asymmetry-densities implied by the spectator reactions that are in thermal equilibrium in different temperature ranges relevant for leptogenesis. [10] Indeed, we found that the largest of theses new effects would barely reach the level of a few tens of percent.

However, two important ingredients had been overlooked in practically all previous studies, and had still to be accounted for. These were the role of the light lepton flavors, and the role of the heavier seesaw Majorana neutrinos. One remarkable exception was the 1999 paper by Barbieri *et al.* [11] that, besides addressing as the main topic the issue of flavor effects in leptogenesis, also pointed out that the lepton number asymmetries generated in the decays of the heavier seesaw neutrinos can contribute to the final value of the BAU.[a] However, these important results did not have much impact on subsequent analyses. The reason might be that these were thought to be just order one effects on the final value of the lepton asymmetry, with no other major consequences for leptogenesis. As I will discuss in the following, the size of the effects could easily reach the one order of magnitude level and, most importantly, they can spoil the leptogenesis constraints on the neutrino low energy parameters, and in particular the limit on the absolute scale of neutrino masses. [13] This is important, since it was thought that this limit was a firm prediction of leptogenesis with hierarchical seesaw neutrinos, and that the discovery of a neutrino mass $m_\nu \gtrsim 0.2\,\mathrm{eV}$ would have strongly disfavored leptogenesis, or hinted to different scenarios (as e.g. resonant leptogenesis [14]).

2 The standard scenario

Let us start by writing the first few terms of the leptogenesis Lagrangian, neglecting for the moment the heavier neutrinos $N_{2,3}$ (except for their virtual effects in the CP violating asymmetries):

$$\mathcal{L} = \frac{1}{2}\left[\bar{N}_1(i\,\not{\partial})N_1 - M_1 N_1 N_1\right] - (\lambda_1\,\bar{N}_1\,\ell_1 H + \text{h.c.}). \tag{1}$$

[a] Lepton flavor effects were also considered by Endoh, Morozumi and Xiong in their 2003 paper, [12] in the context of the minimal seesaw model with just two right handed neutrinos.

Here N_1 is the lightest right-handed Majorana neutrino with mass M_1, H is the Higgs field, and ℓ_1 is the lepton doublet to which N_1 couples, that when expressed on a complete orthogonal basis $\{\ell_i\}$ reads

$$|\ell_1\rangle = (\lambda\lambda^\dagger)_{11}^{-1/2} \sum_i \lambda_{1i} |\ell_i\rangle. \tag{2}$$

In practice it is always convenient to use the basis that diagonalizes the charged lepton Yukawa couplings (the flavor basis) that also has well defined CP conjugation properties $CP(\{\ell_i\}) = \{\bar{\ell}_i\}$ with $i = e, \mu, \tau$. Note that in the first and third term in (1) a lepton number can be assigned to N_1, that is however violated by two units by the mass term. Then eq. (1) implies processes that violate L, like inverse-decays followed by N_1 decays $\ell_1 \leftrightarrow N_1 \leftrightarrow \bar{\ell}_1$, off-shell $\Delta L = 2$ scatterings $\ell_1 H \leftrightarrow \bar{\ell}_1 \bar{H}$, $\Delta L = 1$ scatterings involving the top-quark like $N_1 \ell_1 \leftrightarrow Q_3 \bar{t}$ or involving the gauge bosons like $N_1 \ell_1 \to A\bar{H}$ (with $A = W_i, B$). The temperature range in which $\not{L}$ processes can be important for leptogenesis is around $T \sim M_1$. This is because if the λ_1 couplings were large enough that these processes were already relevant at $T \gg M_1$ (when the Universe expansion is fast) than they would come into complete thermal equilibrium at lower temperatures (when the expansion slows down) thus forbidding the survival of any macroscopic L asymmetry. On the other hand at $T \ll M_1$ decays, inverse decays and $\Delta L = 1$ scatterings are Boltzmann suppressed, $\Delta L = 2$ scatterings are power suppressed, and therefore L violating processes become quite inefficient as the temperature drops well below M_1.

The possibility of generating an asymmetry between the number of leptons n_{ℓ_1} and antileptons $n_{\bar{\ell}_1}$ is due to a non-vanishing CP asymmetry in N_1 decays:

$$\epsilon_1 \equiv \frac{\Gamma(N_1 \to \ell_1 H) - \Gamma(N_1 \to \bar{\ell}_1 \bar{H})}{\Gamma(N_1 \to \ell_1 H) + \Gamma(N_1 \to \bar{\ell}_1 \bar{H})} \neq 0. \tag{3}$$

In order that a macroscopic L asymmetry can build up, the condition that $\not{L}$ reactions are (at least slightly) out of equilibrium at $T \sim M_1$ must also be satisfied. This condition can be expressed in terms of two dimensionfull parameters, defined in terms of the Higgs vev $v \equiv \langle H \rangle$ and of the Plank mass M_P as:

$$\tilde{m}_1 = \frac{(\lambda\lambda^\dagger)_{11}\, v^2}{M_1}, \qquad m_* \approx 10^3 \frac{v^2}{M_P} \approx 10^{-3}\,\text{eV}. \tag{4}$$

The first parameter ($\tilde{m}_1$) is related to the rates of N_1 processes (like decays and inverse decays) while the second one (m_*) is related to the expansion rate of the Universe at $T \sim M_1$. When $\tilde{m}_1 \lesssim m_*$, $\not{L}$ processes are slower than the Universe expansion rate and leptogenesis can occur. As $\tilde{m}_1$ increases to values larger than m_*, $\not{L}$ reactions approach thermal equilibrium thus rendering leptogenesis inefficient because of the back-reactions that tend to erase any macroscopic asymmetry. However, even for $\tilde{m}_1$ as large as $\sim 100\, m_*$ a lepton asymmetry sufficient to explain the BAU can be generated. It is customary to refer to the condition $\tilde{m}_1 > m_*$ as to the *strong washout regime* since washout reactions are rather fast. This regime is considered more likely than the *weak washout regime* $\tilde{m}_1 < m_*$ in view of the experimental values of the light neutrino mass-squared differences (that are both $> m_*^2$) and of the theoretical lower bound $\tilde{m}_1 \geq m_{\nu_1}$, where m_{ν_1} is the mass of the lightest neutrino. The strong washout regime is also theoretically more appealing since the final value of the lepton asymmetry is independent of the particular value of the N_1 initial abundance, and also of a possible asymmetry $Y_{\ell_1} = (n_{\ell_1} - n_{\bar{\ell}_1})/s \neq 0$ (where s is the entropy density) preexisting the N_1 decay era. This last fact has been often used to argue that for $\tilde{m}_1 > m_*$ only the dynamics of the lightest Majorana neutrino N_1 is important, since asymmetries generated in the decays of the heavier $N_{2,3}$ would be efficiently erased by the strong N_1-related washouts. As we will see below, the effects of N_1 interactions on the $Y_{\ell_{2,3}}$ asymmetries are subtle, and the previous argument is incorrect. The result of numerical

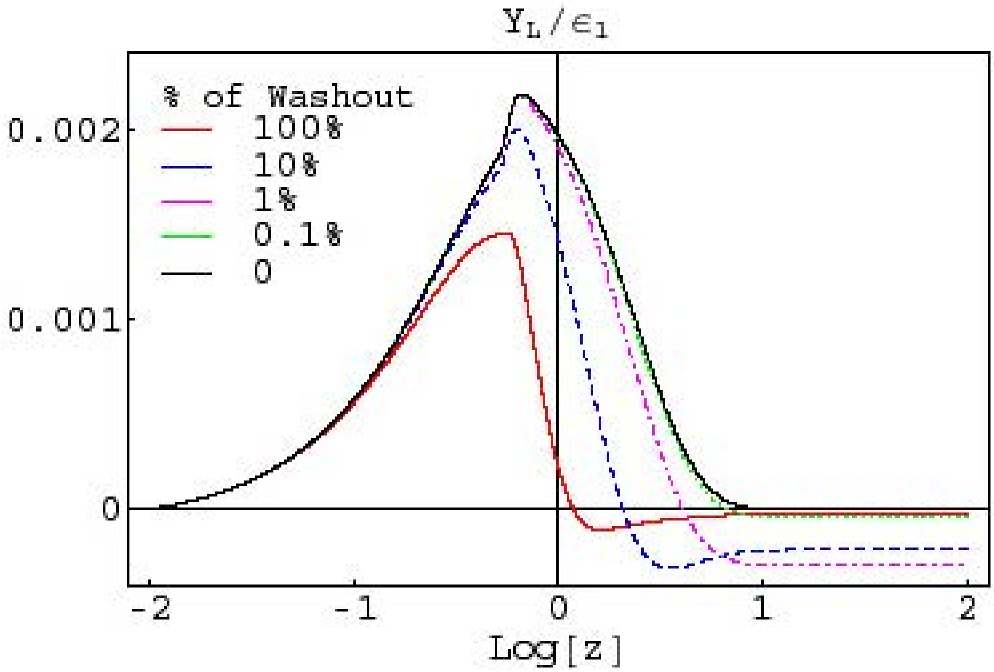

Figure 1: Evolution of the lepton asymmetry plotted against $z = M_1/T$. The different curves depict the effects of reducing progressively the rates of the washout processes (as detailed in the legend). Complete switch off of the washouts (thin solid black line) yields a vanishing lepton asymmetry.

integration of the Boltzmann equations for Y_{ℓ_1} can be conveniently expressed in terms of an efficiency factor η_1, that ranges between 0 and 1:

$$Y_{\ell_1} = 3.9 \times 10^{-3}\, \eta_1 \epsilon_1, \qquad \eta_1 \approx \frac{m_*}{\tilde{m}_1}. \tag{5}$$

The second relation gives a rough approximation for η_1 in the strong washout regime, that will become useful in analyzing the impact of flavor effects. Clearly, too strong washouts ($\tilde{m}_1 \gg m_*$) can put in jeopardy the success of leptogenesis by suppressing too much the efficiency. However, it should also be stressed that washouts constitute a fundamental ingredient to generate a lepton asymmetry. This is particularly true in thermal leptogenesis, with zero initial N_1 abundance, and is illustrated in fig. 1 where the evolution of the lepton asymmetry for a representative model is plotted against decreasing values of the temperature. The different curves correspond to different level of (artificial) reduction in the strength of the washout rates (but not in the N_1 production rates) from the model value (solid red line), to 10% (dashed blue line), 1% (dot-dashed pink line) and 0.1% (dotted green line). The solid black line corresponds to switching off all back-reactions. (Of course the last four curves correspond to unphysical conditions.) It is apparent that while a partial reduction in the washout rates is beneficial to leptogenesis, an excessive reduction suppresses the final asymmetry and eventually, when washouts are switched off completely, no asymmetry survives. This behavior can be understood as follows: all leptogenesis processes can be seen as scatterings between standard model particle states X, Y involving intermediate on-shell and off-shell unstable N_1's: $X \leftrightarrow N_1^{(*)} \leftrightarrow Y$. Since the CP asymmetry of any $X \leftrightarrow Y$ process is at most of $\mathcal{O}(\lambda^6)$[15], if the lepton asymmetries generated in the different processes were exactly conserved, the overall amount that could survive would not exceed this order. Moreover, since $\mathcal{O}(\lambda_1^6)$ asymmetries are systematically neglected in the Boltzmann equations, the numerical result would be exactly zero. However, the on-shell and off-shell components of each process have much larger CP asymmetries of $\mathcal{O}(\lambda_1^4)$, and the cancellation to $\mathcal{O}(\lambda_1^6)$ occurs because they are of opposite sign and (at leading order in the couplings) of the same magnitude. Moreover, since the long range and short range components of each process have different time scales, at each instant during leptogenesis a lepton asymmetry up to $\mathcal{O}(\lambda_1^4)$ can be present. Washout processes by definition do not conserve the lepton asymmetries, and most importantly they act unevenly over the different processes as well as over their short and long range components, erasing more efficiently the asymmetries generated in N_1 production processes and off-shell scatterings that on average occur at earlier times, and washing out less efficiently the asymmetries of processes that destroy N_1's (on-shell scatterings and decays). It is thanks to the washouts that an unbalanced lepton asymmetry up to $\mathcal{O}(\lambda_1^4)$ can eventually survive. In the next section we will see that when flavor effects are important, washouts can play an even more dramatic role in leptogenesis.

The possibility of deriving an upper limit for the the light neutrino masses [13] follows from the existence of a theoretical bound on the maximum value of the CP asymmetry ϵ_1 (that holds when $N_{1,2,3}$ are sufficiently hierarchical, and $m_{\nu_{1,2,3}}$ quasi degenerate) and relates M_1, m_{ν_3} and the washout parameter $\tilde{m}_1$:

$$|\epsilon_1| \leq \left[\frac{3}{16\pi}\frac{M_1}{v^2}(m_{\nu_3} - m_{\nu_1})\right] \sqrt{1 - \frac{m_{\nu_1}^2}{\tilde{m}_1^2}}. \tag{6}$$

The term in square brackets is the so called Davidson-Ibarra limit [16] while the correction in the square root was first given in ref..[17] When $m_{\nu_3} \gtrsim 0.1\,\text{eV}$, the light neutrinos are quasi-degenerate and $m_{\nu_3} - m_{\nu_1} \sim \Delta m^2_{atm}/2m_{\nu_3} \to 0$ so that, to keep ϵ_1 finite, M_1 is pushed to large values $\gtrsim 10^{13}\,\text{GeV}$. Since at the same time $\tilde{m}_1$ must remain larger than m_{ν_1} the washouts also increase, until the surviving asymmetry is too small to explain the BAU.[b] The limit $m_{\nu_3} \lesssim 0.15\,\text{eV}$ results.

3 Lepton flavor effects

In the Lagrangian (1) the terms involving the charged lepton Yukawa couplings have not been included. Since all these couplings are rather small, if leptogenesis occurs at temperatures $T \gtrsim 10^{12}\,\text{GeV}$, when the Universe is still very young, not many of the related (slow) processes could have occurred during its short lifetime, and leptogenesis has essentially no knowledge of lepton flavors. At $T \lesssim 10^{12}\,\text{GeV}$ the reactions mediated by the tau Yukawa coupling h_τ become important, and at $T \lesssim 10^9\,\text{GeV}$ also h_μ-reactions have to be accounted for. Including the Yukawa terms for the leptons yields the Lagrangian:

$$\mathcal{L} = \frac{1}{2}\left[\bar{N}_1(i\,\partial\!\!\!/)N_1 - M_1 N_1 N_1\right] - (\lambda_{1i}\bar{N}_1\,\ell_i H + h_i \bar{e}_i \ell_i H^\dagger + \text{h.c.}), \tag{7}$$

where (in the flavor basis) the matrix h of the Yukawa couplings is diagonal. The flavor content of the (anti)lepton doublets ℓ_1 ($\bar{\ell}'_1$) to which N_1 decays is now important, since these states do not remain coherent, but are effectively resolved into their flavor components by the fast Yukawa interactions h_i.[11,18,19] Note that because of CP violating loop effects, in general $CP(\bar{\ell}'_1) \neq \ell_1$, that is the antileptons produced in N_1 decays are not the CP conjugated of the leptons, implying that the flavor projections $K_i \equiv |\langle\ell_i|\ell_1\rangle|^2$ and $\bar{K}_i \equiv |\langle\bar{\ell}_i|\bar{\ell}'_1\rangle|^2$ differ: $\Delta K_i = K_i - \bar{K}_i \neq 0$. The flavor CP asymmetries can be defined as: [19]

$$\epsilon_1^i = \frac{\Gamma(N_1 \to \ell_i H) - \Gamma(N_1 \to \bar{\ell}_i \bar{H})}{\Gamma_{N_1}} = K_i \epsilon_1 + \Delta K_i/2. \tag{8}$$

The factor ΔK_i in the second equality accounts for the flavor mismatch between leptons and antileptons. The factor K_i in front of ϵ_1 accounts for the reduction in the strength of the N_1-ℓ_i

[b] $\Delta L = 2$ washout processes, that depend on a different parameter than $\tilde{m}_1$, and that can become important when M_1 is large, also play a role in establishing the limit.

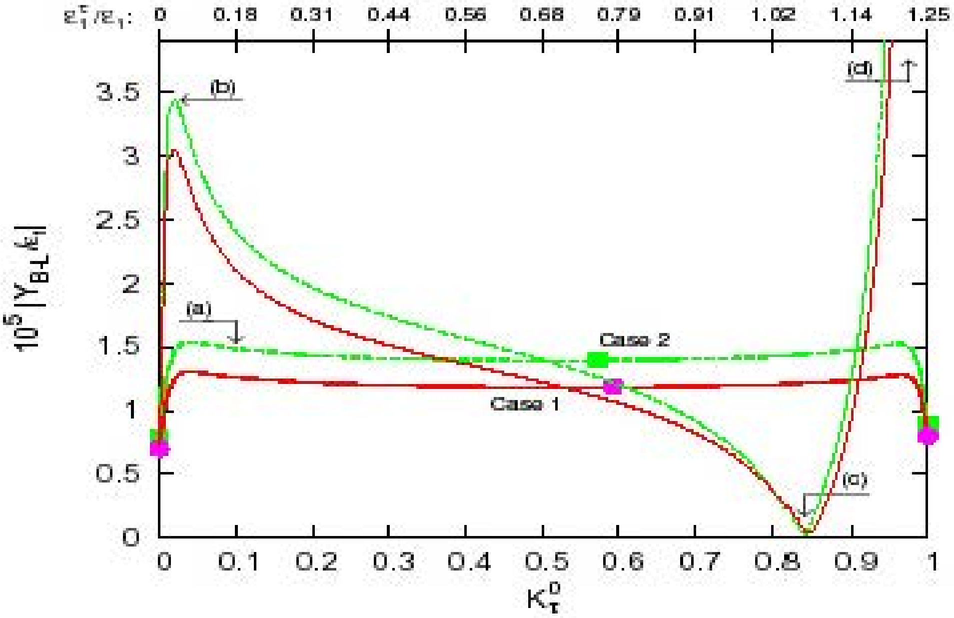

Figure 2: $|Y_{B-L}|$ (in units of $10^{-5}|\epsilon_1|$) as a function of K_τ in two two-flavor regimes. The thick solid and dashed lines correspond to the special case when $K_\tau = \bar{K}_\tau$. The two thin lines give an example of the results for $K_\tau \neq \bar{K}_\tau$. The filled circles and squares at $K_\tau = 0, 1$ correspond to the aligned cases where flavor effects are irrelevant.

coupling with respect to N_1-ℓ_1, and thus reduces also the strength of the washouts for the i-flavor, yielding an efficiency factor $\eta_1^i = \min(\eta_1/K_i, 1)$. Assuming for illustration $\eta_1/K_i < 1$ the resulting asymmetry is

$$Y_L \approx \sum_i \epsilon_1^i \eta_1^i \approx n_f Y_{\ell_1} + \sum_i \frac{\Delta K_i}{2K_i} \frac{m_*}{\tilde{m}_1}. \tag{9}$$

In the first term on the r.h.s. n_f represents the number of flavors effectively resolved by the charged lepton Yukawa interactions ($n_f = 2$ or 3) while Y_{ℓ_1} is the asymmetry that would have been obtained by neglecting the decoherence of ℓ_1. The second term, that is controlled by the 'flavor mismatch' factor ΔK_i, can become particularly large in the cases when the flavor i is almost decoupled from N_1 ($K_i \ll 1$). This situation is depicted in fig. 2 for the two-flavor case and for two different temperature regimes. The two flat curves give $|Y_{B-L}|$ as a function of the flavor projector K_τ assuming $\Delta K_\tau = 0$, and show rather clearly the enhancement of a factor ≈ 2 with respect to the one flavor case (the points at $K_\tau = 0, 1$). The other two curves are peaked at values close to the boundaries, when ℓ_τ or a combination orthogonal to ℓ_τ are almost decoupled from N_1, and show how the ℓ_1-ℓ_1' flavor mismatch can produce much larger enhancements.

It was first noted in ref.[19] that flavored-leptogenesis can be viable even when the branching ratios for decays into leptons and antileptons are equal, that is in the limit when L is conserved in decays and the total asymmetry $\epsilon_1 = 0$ vanishes. This is a surprising possibility, that can occur when the CP asymmetries for the single flavors are non-vanishing, thanks to the fact that lepton number is in any case violated by the washout interactions.

In conclusion, the relevance of flavor effects is at least twofold:

1. The BAU resulting from leptogenesis can be several times larger than what would be obtained neglecting flavor effects.

2. If leptogenesis occurs at temperatures when flavor effects are important, the limit on the light neutrino masses does not hold.[18,20] This is because there is no analogous of the Davidson-Ibarra bound in eq. (6) for the flavor asymmetries ϵ_1^i.

4 The effects of the heavier Majorana neutrinos

What about the possible effects of the heavier Majorana neutrinos $N_{2,3}$ that we have so far neglected? A few recent studies analyzed the so called "N_1-decoupling" scenario, in which the Yukawa couplings of N_1 are simply too weak to washout the asymmetry generated in N_2 decays (and ϵ_1 is too small to explain the BAU).[21] This is a consistent scenario in which N_2 leptogenesis could successfully generate enough lepton asymmetry. However, in the opposite situation when the Yukawa couplings of N_1 are very large, it was generally assumed that the asymmetries related to $N_{2,3}$ are irrelevant, since they would be washed out during N_1 leptogenesis. In contrast to this, in ref. [11] (and more recently also in ref. [22]) it was stated that part of the asymmetry from $N_{2,3}$ decays does in general survive, and must be taken into account when computing the BAU. In ref. [23] Engelhard, Grossman, Nir and myself carried out a detailed study of the fate of a lepton asymmetry Y_P preexisting N_1 leptogenesis, and we reached conclusions that agree with these statements. I will briefly describe the reasons for this and the importance of the results. Including also $N_{2,3}$ the leptogenesis Lagrangian reads:

$$\mathcal{L} = \frac{1}{2}\left[\bar{N}_\alpha(i\partial\!\!\!/)N_\alpha - N_\alpha M_\alpha N_\alpha\right] - (\lambda_{\alpha i}\bar{N}_\alpha \ell_i H + h_i \bar{e}_i \ell_i H^\dagger + \text{h.c.}), \tag{10}$$

where the heavy neutrinos are written in the mass basis with $\alpha = 1, 2, 3$. It is convenient to define the three (in general non-orthogonal) combinations of lepton doublets ℓ_α to which the corresponding N_α decay:

$$|\ell_\alpha\rangle = (\lambda\lambda^\dagger)^{-1/2}_{\alpha\alpha} \sum_i \lambda_{\alpha i}|\ell_i\rangle. \tag{11}$$

Let us discuss for definiteness the case when N_2-related washouts are not too strong ($\tilde{m}_2 \not\gg m_*$) , so that a sizeable asymmetry proportional to ϵ_2 is generated, while N_1-related washouts are so strong that by itself N_1 leptogenesis would not be successful ($\tilde{m}_1 \gg m_*$). To simplify the arguments, let us also impose two additional conditions: thermal leptogenesis, that is a vanishing initial N_1 abundance $n_{N_1}(T \gg M_1) \approx 0$, and a strong hierarchy $M_2/M_1 \gg 1$. From this it follows that there are no N_1 related washout effects during N_2 leptogenesis and, because $n_{N_2}(T \approx M_1)$ is Boltzmann suppressed, there are no N_2 related washouts during N_1 leptogenesis. Thus N_2 and N_1 dynamics are decoupled. Now, the second condition in (??) implies that already at $T \gtrsim M_1$ the interactions mediated by the N_1 Yukawa couplings are sufficiently fast to quickly destroy the coherence of ℓ_2 produced in N_2 decays. Then a statistical mixture of ℓ_1 and of states orthogonal to ℓ_1 builds up, and it can be described by a suitable *diagonal* density matrix. For simplicity, let us assume that both N_2 and N_1 decay at $T \gtrsim 10^{12}$ GeV when flavor effects are irrelevant. In this regime a convenient choice for the orthogonal lepton basis is $(\ell_1, \ell_{1_\perp})$ where $\ell_{1_\perp}$ denotes generically the flavor components orthogonal to ℓ_1. Then any asymmetry Y_P preexisting the N_1 leptogenesis phase (as for example Y_{ℓ_2}) decomposes as:

$$Y_P = Y_{\ell_{1_\perp}} + Y_{\ell_1}. \tag{12}$$

The crucial point here is that in general we can expect $Y_{\ell_{1_\perp}}$ to be of the same order than Y_P, and since $\ell_{1_\perp}$ is orthogonal to ℓ_1, this component of the asymmetry remains protected against N_1 washouts. Therefore, a finite part of any preexisting asymmetry (and in particular of Y_{ℓ_2} generated in N_2 decays) survives through N_1 leptogenesis. A more detailed study[23] reveals also some additional features. For example, in spite of the strong N_1-related washouts Y_{ℓ_1} is not driven to zero, rather, only the sum of Y_{ℓ_1} and of the Higgs asymmetry Y_H vanishes, but not the two separately. (This can be traced back to the presence of a conserved charge related to $Y_{\ell_{1_\perp}}$.)

For $10^9 \lesssim M_1 \lesssim 10^{12}$ GeV the lepton flavor structures are only partially resolved during N_1 leptogenesis, and a similar result is obtained. However, when $M_1 \lesssim 10^9$ GeV and the full flavor basis $(\ell_e, \ell_\mu, \ell_\tau)$ is resolved, there are no directions in flavor space where an asymmetry can remain protected, and then Y_P can be completely erased independently of its flavor composition. In conclusion, the common assumption that when N_1 leptogenesis occurs in the strong washout regime the final BAU is independent of initial conditions, does not hold in general, and is justified only in the following cases: [23] *i)* Vanishing decay asymmetries and/or efficiency factors for $N_{2,3}$ ($\epsilon_2\eta_2 \approx 0$ and $\epsilon_3\eta_3 \approx 0$); *ii)* N_1-related washouts are still significant at $T \lesssim 10^9$ GeV; *iii)* Reheating occurs at a temperature in between M_2 and M_1. In all other cases the initial conditions for N_1 leptogenesis, and in particular those related to the possible presence of an initial asymmetry from $N_{2,3}$ decays, cannot be ignored when calculating the BAU, and any constraint inferred from analyses based only on N_1 leptogenesis are not reliable.

Acknowledgments

This contribution is based on work done in collaboration with G. Engelhard, Y. Grossman, Y. Nir, J. Racker and E. Roulet. I acknowledge partial support from INFN in Italy and from Colciencias in Colombia under contract No. 1115-333-18739.

References

1. M. Fukugita and T. Yanagida, *Phys. Lett.* B **174**, 45 (1986).
2. V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, *Phys. Lett.* B **155**, 36 (1985).
3. G. R. Farrar and M. E. Shaposhnikov, *Phys. Rev. Lett.* **70**, 2833 (1993); [Erratum-ibid. **71**, 210 (1993)].
4. M. B. Gavela, P. Hernandez, J. Orloff and O. Pene, *Mod. Phys. Lett.* A **9**, 795 (1994); *Nucl. Phys.* B **430**, 345 (1994); M. B. Gavela *et al.*, *Nucl. Phys.* B **430**, 382 (1994); P. Huet and E. Sather, *Phys. Rev.* D **51**, 379 (1995).
5. M. A. Luty, *Phys. Rev.* D **45**, 455 (1992).
6. L. Covi, E. Roulet and F. Vissani, *Phys. Lett.* B **384**, 169 (1996).
7. E. Nardi, arXiv:hep-ph/0702033.
8. See e.g. C. Balazs *et al.*, proceedings of the 2005 ILC Physics and Detector Workshop and 2nd ILC Accelerator Workshop, Snowmass, Colorado, 14-27 Aug 2005. ECONF C0508141:ALCPG0333,2005.
9. G. F. Giudice *et al.*, *Nucl. Phys.* B **685**, 89 (2004).
10. E. Nardi, Y. Nir, J. Racker and E. Roulet, *JHEP* **0601**, 068 (2006).
11. R. Barbieri, P. Creminelli, A. Strumia and N. Tetradis, *Nucl. Phys.* B **575**, 61 (2000).
12. T. Endoh, T. Morozumi and Z. h. Xiong, *Prog. Theor. Phys.* **111**, 123 (2004).
13. See *e.g.*: W. Buchmuller, P. Di Bari and M. Plumacher, *Phys. Lett.* B **547**, 128 (2002); *Nucl. Phys.* B **665**, 445 (2003).
14. A. Pilaftsis, *Phys. Rev. Lett.* **95**, 081602 (2005); A. Pilaftsis and T. E. J. Underwood, *Nucl. Phys.* B **692**, 303 (2004); *Phys. Rev.* D **72**, 113001 (2005).
15. E. W. Kolb and S. Wolfram, Nucl. Phys. B **172**, 224 (1980) [Erratum-ibid. B **195**, 542
16. S. Davidson and A. Ibarra, *Phys. Lett.* B **535**, 25 (2002).
17. T. Hambye *et al.*, *Nucl. Phys.* B **695** (2004) 169.
18. A. Abada *et al.*, *JCAP* **0604**, 004 (2006).
19. E. Nardi, Y. Nir, E. Roulet and J. Racker, *JHEP* **0601**, 164 (2006).
20. A. De Simone and A. Riotto, *JCAP* **0702**, 005 (2007).
21. O. Vives, *Phys. Rev.* D **73**, 073006 (2006); P. Di Bari, *Nucl. Phys.* B **727**, 318 (2005); S. Blanchet and P. Di Bari, *JCAP* **0606**, 023 (2006).
22. A. Strumia, arXiv:hep-ph/0608347.
23. G. Engelhard, Y. Grossman, E. Nardi and Y. Nir, arXiv:hep-ph/0612187.