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Phenomenology of baryogenesis from lepton-doublet mixing

Björn Garbrecht [a,*], Ignacio Izaguirre [a,b]

[a] *Physik Department T70, James-Franck-Straße, Technische Universität München, 85748 Garching, Germany*
[b] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany*

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Abstract

Mixing lepton doublets of the Standard Model can lead to lepton flavour asymmetries in the Early Universe. We present a diagrammatic representation of this recently identified source of *CP* violation and elaborate in detail on the correlations between the lepton flavours at different temperatures. For a model where two sterile right-handed neutrinos generate the light neutrino masses through the see-saw mechanism, the lower bound on reheat temperatures in accordance with the observed baryon asymmetry turns out to be $\gtrsim 1.2 \times 10^9$ GeV. With three right-handed neutrinos, substantially smaller values are viable. This requires however a tuning of the Yukawa couplings, such that there are cancellations between the individual contributions to the masses of the light neutrinos.

1. Introduction

Observational and theoretical studies of mixing and oscillations are typically concerned with neutral particle states. Important examples are neutral meson mixing, the oscillations of Standard Model (SM) neutrinos [1] and Leptogenesis through the mixing of sterile right-handed neutrinos (RHNs) in the early Universe [2–5]. In contrast, for charged particles in the SM at vanishing temperature, mass degeneracies between different states are not strong enough to produce observable

* Corresponding author.
E-mail address: garbrecht@tum.de (B. Garbrecht).

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phenomena of mixing and oscillations. This does however not preclude the fact that these effects are present in principle. Moreover, it has been demonstrated that the mixing of lepton doublets (which are gauged) can be of importance for Leptogenesis [6–10]: At high temperatures, the asymmetries are in general produced as superpositions of the lepton doublet flavour eigenstates of the SM. In the SM flavour basis, this can be described in terms of off-diagonal correlations in the two-point functions, or alternatively in effective density-matrix formulations in terms of correlations of charge densities of different flavours. At smaller temperatures, interactions mediated by SM Yukawa couplings become faster than the Hubble expansion, such that the flavour correlations decohere. In particular, the SM leptons receive thermal mass corrections as well as damping rates that lift the flavour degeneracy. By now, these effects have been investigated in detail. It turns out that due to the interplay with gauge interactions, the flavour oscillations that may be anticipated from the thermal masses are effectively frozen, while the decoherence proceeds mainly through the damping effects, *i.e.* the production and the decay of leptons in the plasma [9,10]. The appropriate treatment of these flavour correlations turns out to be of leading importance for the washout of the asymmetries from the out-of-equilibrium decays and inverse decays of the RHNs.

The origin of the charge–parity (*CP*) asymmetry for Leptogenesis is usually attributed to the RHNs and their couplings [11]. In the standard calculation, when describing the production and the decay of the RHNs through S-matrix elements, one can diagrammatically distinguish between vertex and wave-function terms. The presence of finite-temperature effects as well as the notorious problem of correctly counting real intermediate states in the Boltzmann equations [12] have motivated the use of techniques other than the S-matrix approach: It has been demonstrated that the wave-function contribution can alternatively be calculated by solving kinetic equations (that are Kadanoff–Baym type equations which descend from Schwinger–Dyson equations, see Refs. [13–17] on the underlying formalism) for the RHNs and their correlations, or equivalently, by solving for the evolution of their density matrix [18–25]. The vertex contributions to the decay asymmetry can be obtained within the Kadanoff–Baym framework as well, as it is shown in Refs. [26–32]. We note at this point that it has more recently been argued that the asymmetry from the wave-function correction and the contribution from the kinetic equation are distinct contributions that should be added together [33,34]. However, it is shown in Refs. [19–21] that the kinetic equations derived from the two-particle irreducible effective action capture all contributions of relevance for the *CP* asymmetry at leading order, which also encompasses the wave-function corrections.

The calculations for Leptogenesis based on Schwinger–Dyson equations on the Closed-Time-Path (CTP) can also be applied to Leptogenesis from oscillations of light (masses much below the temperature) RHNs [35], also known as the ARS scenario after the authors of Ref. [36]. In this approach, we can interpret the *CP* violation as originating from cuts of the one-loop self-energy of the RHNs, that are dominantly thermal. It can be concluded that thermal effects can largely open the phase–space for *CP*-violating cuts that are strongly suppressed for kinematic reasons at vanishing temperature.

Putting together the elements of flavour correlations for charged particles and of thermal cuts, we can identify new sources for the lepton asymmetry, in addition to the one from cuts in the RHN propagator. In models with multiple Higgs doublets, Higgs bosons may be the mixing particles [37], whereas in minimal type-I see-saw scenarios (with one Higgs doublet), this role can be played by mixing SM lepton doublets [38]. Yet, the RHNs remain of pivotal importance because due to their weak coupling, they provide the deviation from thermal equilibrium that is necessary for any scenario of baryogenesis.