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Flavour covariant transport equations: An application to resonant leptogenesis

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Abstract

We present a *fully* flavour-covariant formalism for transport phenomena, by deriving Markovian master equations that describe the time-evolution of particle number densities in a statistical ensemble with arbitrary flavour content. As an application of this general formalism, we study flavour effects in a scenario of resonant leptogenesis (RL) and obtain the flavour-covariant evolution equations for heavy-neutrino and lepton number densities. This provides a complete and unified description of RL, capturing three *distinct* physical phenomena: (i) the resonant mixing between the heavy-neutrino states, (ii) coherent oscillations between different heavy-neutrino flavours, and (iii) quantum decoherence effects in the charged-lepton sector. To illustrate the importance of this formalism, we numerically solve the flavour-covariant rate equations for a minimal RL model and show that the total lepton asymmetry can be enhanced by up to one order of magnitude, as compared to that obtained from flavour-diagonal or partially flavour off-diagonal rate equations. Thus, the viable RL model parameter space is enlarged, thereby enhancing further the prospects of probing a common origin of neutrino masses and the baryon asymmetry in the Universe at the LHC, as well as in low-energy experiments searching for lepton flavour and number violation. The key new ingredients in our flavour-covariant formalism are rank-4 rate tensors, which are required for the consistency of our flavour-mixing treatment, as shown by an explicit calculation of the relevant transition amplitudes by generalizing the optical theorem. We also provide a geometric and physical interpretation of the heavy-neutrino degeneracy limits in the minimal RL scenario. Finally, we comment on the consistency of various suggested forms for the heavy-neutrino self-energy regulator in the lepton-number conserving limit.

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1. Introduction

The observed matter–antimatter asymmetry in the Universe and the observation of non-zero neutrino masses and mixing (for a review, see [1]) provide two of the strongest pieces of experimental evidence for physics beyond the Standard Model (SM). Leptogenesis [2] is an elegant framework that satisfies the basic Sakharov conditions [3], dynamically generating the observed matter–antimatter asymmetry. According to the standard paradigm of leptogenesis (for reviews, see e.g. [4–7]), there exist heavy Majorana neutrinos in minimal extensions of the SM, whose out-of-equilibrium decays in an expanding Universe create a net excess of lepton number (L), which is reprocessed into the observed baryon number (B) through the equilibrated $(B + L)$-violating electroweak sphaleron interactions [8]. In addition, these heavy SM-singlet Majorana neutrinos N_α (with $\alpha = 1, \dots, \mathcal{N}_N$) could explain the observed smallness of the light neutrino masses by the seesaw mechanism [9–13]. Hence, leptogenesis can be regarded as a cosmological consequence of the seesaw mechanism, thus providing an attractive link between two seemingly disparate pieces of evidence for new physics at or above the electroweak scale.

In the original scenario of thermal leptogenesis [2], the heavy Majorana neutrino masses are typically close to the Grand Unified Theory (GUT) scale, $M_{\rm GUT} \sim 10^{16}$ GeV, as suggested by natural GUT embedding of the seesaw mechanism [10–12]. In a 'vanilla' leptogenesis scenario [14], where the heavy neutrino masses are hierarchical ($m_{N_1} \ll m_{N_2} < m_{N_3}$), the solar and atmospheric neutrino oscillation data impose a *lower* limit on $m_{N_1} \gtrsim 10^9$ GeV [15–18]. As a consequence, such leptogenesis models are difficult to test in foreseeable laboratory experiments. Moreover, these high-scale thermal leptogenesis scenarios, when embedded within supergravity models of inflation, could potentially lead to a conflict with the upper bound on the reheating temperature of the Universe, $T_R \lesssim 10^6$–10^9 GeV, required to avoid overproduction of gravitinos whose late decays may otherwise spoil the success of Big Bang Nucleosynthesis [19–25]. In general, it is difficult to build a *testable* low-scale model of leptogenesis, with a hierarchical heavy neutrino mass spectrum [4,26].

A potentially interesting solution to the aforementioned problems may be obtained within the framework of resonant leptogenesis (RL) [27–29]. The key aspect of RL is that the heavy Majorana neutrino self-energy effects [30] on the leptonic *CP*-asymmetry become dominant [31, 32] and get resonantly enhanced, even up to order one [27,28], when at least two of the heavy neutrinos have a small mass difference comparable to their decay widths. As a consequence of thermal RL, the heavy Majorana neutrino mass scale can be as low as the electroweak scale [33], while maintaining complete agreement with the neutrino oscillation data [1].

A crucial model-building aspect of RL is the *quasi-degeneracy* of the heavy neutrino mass spectrum, which could be obtained as a natural consequence of the approximate breaking of some symmetry in the leptonic sector. In minimal extensions of the SM, there is no theoretically or phenomenologically compelling reason that prevents the singlet neutrino sector from possessing such a symmetry and, in fact, in realistic ultraviolet-complete extensions of the SM, such a symmetry can often be realized naturally. For instance, the RL model discussed in [27,28] was based on a $U(1)_L$ lepton symmetry in the heavy neutrino sector, motivated by superstring-inspired E_6 GUTs [34–36]. The small mass splitting between the heavy neutrinos was generated by approximate breaking of this lepton symmetry via GUT- and/or Planck-scale-suppressed