Non-relativistic Majorana neutrinos in a thermal bath and leptogenesis

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Neutrino oscillations, the evidence of dark matter and the baryon asymmetry in the universe can not be explained by the standard model of particle physics. Majorana fermions enter in many scenarios of physics beyond the standard model. For example, in the simplest leptogenesis framework, heavy Majorana neutrinos are at the origin of the baryon asymmetry. In the strong wash-out regime non-relativistic Majorana neutrinos produce the lepton asymmetry that is partially reprocessed into a baryon asymmetry. Moreover, all the interactions occur in a thermal medium, namely the universe in its early stage. We discuss an effective field theory approach to study the dynamics of non-relativistic Majorana particles in a thermal bath made of standard model particles. In particular, the decay width of Majorana neutrinos and the CP asymmetries are key ingredients for most leptogenesis models. We address the derivation of such quantities at finite temperature. We provide a formalism to calculate the thermal corrections to the CP asymmetry in the case of a hierarchical mass spectrum for heavy Majorana neutrinos.

1 Motivation and introduction

The standard model (SM) of particle physics can explain almost all the available experimental data and observations. However, few remarkable evidences, such as the dark matter and the baryon asymmetry in the universe, demand for new physics. Let us focus on the existing imbalance between matter and anti-matter in the universe that may be expressed in terms of the baryon to photon ratio [1]

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10} \,. \tag{1}$$

It is not possible to reproduce such a value within the SM, being its CP violating source too small [2]. Many models for the dynamical generation of the baryon asymmetry have been proposed. Among those leptogenesis [3] is both theoretically and phenomenologically interesting since one can make some connections with the low-energy neutrino physics [4]. In the leptogenesis framework a lepton asymmetry is generated by the CP violating decays of heavy Majorana neutrinos into leptons and anti-leptons in different amounts. These heavy states can in principle explain the smallness of the SM neutrinos via the see-saw mechanism. The net lepton asymmetry is then partially reprocessed into a baryon asymmetry through the so called sphalerons transitions.

In the simplest realization of leptogenesis, the lepton asymmetry is generated by the decay of the lightest heavy Majorana neutrino. The heavier ones decouple earlier from the entire dynamics. One may characterize the properties of the heavy neutrinos in the thermal bath by exploiting the definition of the *decay parameter* [4], that reads

$$K = \frac{\Gamma(T=0)}{H(T=M_1)} = \frac{\frac{M_1|F_1|^2}{8\pi}}{\sqrt{g_*}1.66\frac{M_1^2}{M_{\rm Pl}}} = \frac{\frac{|F_1|^2 v^2}{M_1}}{8\pi\sqrt{g_*}1.66\frac{v^2}{M_{\rm Pl}}} = \frac{\tilde{m}_1}{m_*} \,. \quad (2)$$

The $\Gamma(T=0) \equiv \Gamma_0$ is the in-vacuum total decay width of the heavy Majorana neutrino and $H(T=M_1)$ the Hubble rate evaluated at a temperature of the order of the heavy neutrino mass, M_1. As shown in (2), the decay parameter can be also written in terms of low-energy neutrino quantities where F_1 is the Yukawa coupling between the heavy Majorana neutrino and SM Higgs and lepton doublet, g_* is the effective number of relativistic particles at $T \sim M_1$, $M_{\rm Pl}$ is the Planck scale, v^2 is the electroweak vacuum expectation value and $m_* \simeq 1.1$ eV. According to the neutrino oscillation experiments, one can choose the scale for $\tilde{m}_1$ to be $\mathcal{O}(10)$ eV (according to solar neutrino mass difference). This estimation provides an important information: the lightest heavy neutrinos remain coupled with the SM bath even after the temperature of the cooling system has dropped below the scale M_1. Therefore, the final lepton asymmetry is generated when the heavy neutrinos are non-relativistic. We refer to this scenario as strong wash-out regime [4]. In the next two sections, we show how the effective field theory (EFT) approach may help to address the dynamics of non-relativistic Majorana fermions in a thermal bath. Indeed we may explore the following hierarchy of scales $M_1 \gg T \gg M_W$, where the M_W represents the electroweak scale. The last inequality is well satisfied in the leptogenesis scenario under consideration.

2 Thermal width in the EFT framework

In this section we derive the heavy neutrino thermal width, already calculated in [5] and [6], by using an EFT approach. The thermal corrections to the width are induced by the SM particles in the thermal bath and the calculation in a fully relativistic thermal field theory framework requires the evaluation of two-loop diagrams at finite temperature. On the other hand, by exploiting the EFT, one can split the calculation into two steps: the first one-loop computation is required to match the full theory with the EFT. This can be done setting the temperature to zero, so it amounts at the calculation of typical in-vacuum matrix elements. The second one-loop computation is required to calculate the thermal corrections in the EFT. At the accuracy of the result presented here, only tadpole diagrams are involved.

The low-energy Lagrangian contains SM particles and non-relativistic excitations of Majorana neutrinos at typical energies and momenta smaller than M_1. For heavy neutrinos at rest, up to fluctuation much smaller than M_1, the EFT Lagrangian reads

$$\mathcal{L}_{\rm EFT} = N^\dagger \left(i\partial_0 - i\frac{\Gamma_0}{2} \right) N + \frac{\mathcal{L}^{(1)}}{M_1} + \frac{\mathcal{L}^{(2)}}{M_1^2} + \frac{\mathcal{L}^{(3)}}{M_1^3} + \mathcal{O}\left(\frac{1}{M_1^4} \right) , \quad (3)$$

where $\mathcal{L}^{(1)}$, $\mathcal{L}^{(2)}$ and $\mathcal{L}^{(3)}$ contain dimension five, six and seven operators respectively. To show the procedure, we consider the dimension five operator in $\mathcal{L}^{(1)}$. On symmetry grounds, only the operator $a\, N^\dagger N \phi^\dagger \phi$ contributes, where a is the corresponding matching coefficient.

The operator describes the interaction between heavy Majorana neutrinos and SM Higgs at low energies. In order to determine the coefficient a, we consider the heavy neutrino-Higgs scattering both in the fundamental theory and the low-energy, as shown in figure 1. A one-loop calculation at $T = 0$ is necessary to fix $a = -(3/8\pi)\lambda|F_1|^2$, where λ is the Higgs self-coupling.

Finally we compute the thermal correction to the neutrino width by considering the tadpole diagram in the EFT. It describes the thermal modification induced by thermal Higgs bosons. The leading order thermal width reads

$$\Gamma_\phi = 2\frac{\mathrm{Im}\, a}{M_1}\langle\phi^\dagger(0)\phi(0)\rangle_T = -\frac{\lambda|F|^2 M_1}{8\pi}\left(\frac{T}{M_1}\right)^2 \tag{4}$$

where relativistic and thermal corrections factorize as a result of the EFT treatment.

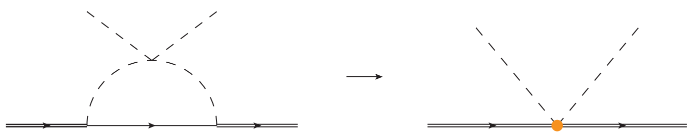

Figure 1: Matching of the dimension five operator. The one-loop process in the fundamental theory is matched onto the effective low-energy interaction. The solid double line stands for the heavy Majorana neutrino, dashed line for Higgs bosons and solid line for SM leptons.

3 CP violating parameter at finite temperature

In this section we want to show how to compute thermal corrections to the CP asymmetry at leading order in the SM couplings. The unflavoured CP asymmetry is defined as follows

$$\epsilon_1 = \sum_f \frac{\Gamma(N_1 \to \ell_f + X) - \Gamma(N_1 \to \bar{\ell}_f + X)}{\Gamma(N_1 \to \ell_f + X) + \Gamma(N_1 \to \bar{\ell}_f + X)} \tag{5}$$

and it arises from the interference between one-loop and tree level diagrams [3]. We focus only on the vertex diagram shown in figure 2 (left diagram). We consider the case of a hierarchically ordered heavy neutrino mass spectrum with two mass eigenstates, M_1 and M_2, such that $M_2 \gg M_1$. At least two neutrinos are needed as one can easily see from the combination of the Yukawa couplings appearing in the $T = 0$ expression for the unflavoured CP asymmetry

$$\epsilon_1 = \frac{\mathrm{Im}\left[(F_1^* F_2)^2\right]}{16\pi|F_1|^2}\left(\frac{M_1}{M_2}\right) + \mathcal{O}\left(\frac{M_1}{M_2}\right)^3 , \tag{6}$$

where we have expanded the known result in [7] according to the hierarchy $M_2 \gg M_1$.

We calculate the leading order thermal correction to the quantity in (6) that arises from the effective low-energy interaction between non-relativistic Majorana neutrino and SM Higgs at energy scales of order $T \ll M_1$. This is done in complete analogy with the thermal width by considering the matching in figure 2. However, there is an important difference with respect to the previous case: we need to construct two subsequent effective theories. We have to integrate

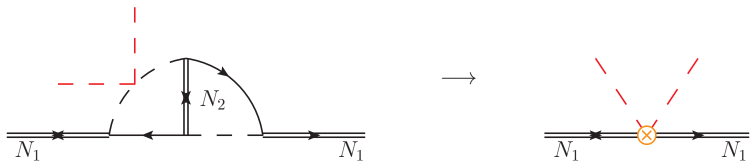

Figure 2: The matching of the fundamental process onto the effective low-energy interaction is shown. The red-dashed lines stand for thermal Higgs bosons from the plasma.

out the energy modes of order M_2 as a first step and integrate out the energy modes of order M_1 in a second stage. Therefore, one is finally left with the proper degrees of freedom: non-relativistic heavy neutrinos that decay and generate the CP asymmetry in a SM thermal bath. The final result is organized according to the power counting of the two effective theories: an expansion in M_1/M_2 and an expansion in T/M_1. It has the form

$$\epsilon_{1,T} \sim \epsilon_1 \, \lambda \left(\frac{T}{M_1} \right)^2 + \cdots \, , \tag{7}$$

where the dots stand for higher orders terms.

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