Matter-antimatter Asymmetry in Preheating

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ABSTRACT

The mechanism of non-perturbative particle production in the preheating era is briefly reviewed. We discuss the possibility of directly generating the matter-antimatter asymmetry through this non- perturbative process. In principle, asymmetry generation is possible if there exists appropriate CP-violating interactions. We show numerical results with a toy model, demonstrating the dynamics. We also show a realistic case in a type-I seesaw model with specific parameters.

INTRODUCTION

In cosmology, inflation and big bang nucleosynthesis (BBN) are strongly supported by current observations. But these two events are not continuous. The temperature of the Universe after inflation would be cold due to the extreme expansion of space, while successful BBN requires a hot Universe with temperatures higher than a few MeV. Moreover, there is no matter-antimatter asymmetry after inflation but only matter appears in the BBN era. Therefore, the Universe must be heated and the asymmetry between matter and the antimatter must be generated by some mechanism after inflation.

A simple story of the (re)heating can be described by the decay of the inflation field into other particles after inflation. Interestingly, however, the "decay" process might be quite different from the normal perturbative picture in some cases [1-4]. To see the specific behavior, let us consider a toy model in which the background field ϕ (classical field) is coupled to a real scalar χ (quantum field), for which the Lagrangian is givern by

$$\mathcal{L}_{\rm int} = -\frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}g^2\phi^2\chi^2 \qquad (1)$$

where m_ϕ and m_χ are masses of ϕ and χ respectively, and g is a coupling constant. For simplicity, we ignore the spatial expansion effect. Especially, in the case of $m_\phi \lesssim M_{\rm eff} \equiv \sqrt{m_\chi^2 + g^2\phi^2}$, the decay of ϕ into χ would be forbidden kinematically. This picture is violated if ϕ is oscillating with a large amplitude. The actual dynamics solved numerically is shown in Figure 1. As one can see, χ particles are produced and are growing exponentially despite $m_\phi < M_{\rm eff}$ at all time. An intuitive understanding for why χ can be produced is that the effective mass of χ, $M_{\rm eff}$, becomes lighter rapidly around $\phi \sim 0$, and hence, the kinetic energy of ϕ can convert to χ easily. The exponential evolution of the number density is explained by another reason. Since equations of motion derived from (1) are described by the Mathieu equation, this system can be analogous with a system consisting of a swing (number density of χ) and a person on the swing (amplitude of ϕ). One can imagine that the person (ϕ) can amplify the amplitude of the swing (χ's number density) by crouching down at the moment when the swing passes the lowest point.

This mechanism occurs before the Universe is thermalized, i.e. in the so-called preheating era. Although the analysis is difficult because of the non-perturbative effect,

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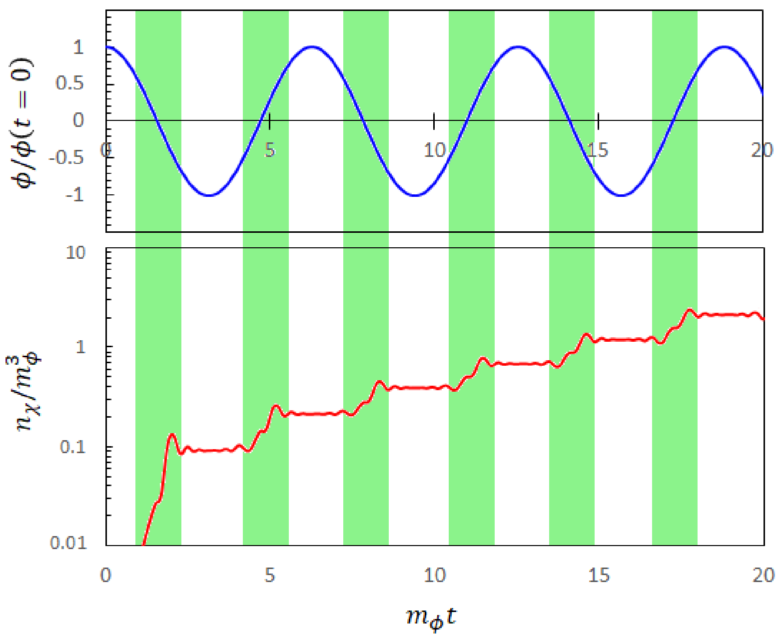

Fig. 1: The time evolution of the amplitude of the background field ϕ and the number density of χ. We chose the parameters as $g = 1$ and $m_\phi = m_\chi = 10^{13}$ GeV and $\phi(t = 0) = 10^{14}$ GeV. The particle production occurs around the points of $\phi \sim 0$ (green regions) at which the effective mass of χ becomes lighter.

the phenomena are quite interesting. In this article, we introduce its application to the generation of the matter-antimatter asymmetry.

ASYMMETRY GENERATION THROUGH THE NON-PERTURBATIVE PROCESS

A lot of studies for the generation of the matter-antimatter asymmetry, so-called baryogenesis, have already been carried out. There are several scenarios associated with preheating [5-7]. A motivation for applying non-perturbative particle production is that the parent particles whose decay can generate baryons tend to be heavier than the inflation field. The non-perturbative process allows the creation of heavier particles, while ordinary reheating theory cannot allow it kinematically. Finally, baryons can be obtained by the perturbative decay of such heavy particles.

In the above scenario, is the process to create heavy particles necessary? Naively, even if the heavy particles do not appear, it seems enough that their decay products are produced with asymmetry. In this situation, non-perturbative particle production and asymmetry production seems to occur simultaneously.

The possibility of asymmetry production through non-perturbative particle production has been discussed in earlier studies [8-10]. The essence to generating asymmetry is that the model has a CP-violating interaction. For example, let us consider the following toy model;

$$\begin{aligned}\mathcal{L} = |\partial\chi|^2 - \left|m_\chi^2(t)\right|\chi\right|^2 + \frac{1}{2}(\partial\eta)^2 - \frac{1}{2}m_\eta^2\eta^2 \\ - \left(\frac{1}{2}\epsilon\chi^2 + g\chi\eta + \text{h.c.}\right)\end{aligned} \tag{2}$$

where χ is a complex scalar and η is a real scalar, and ϵ and g are complex coupling constants. Note that there is a phase remaining in either ϵ or g after field redefinition. Thus CP is violated in this model. If the mass of χ oscillates due to another background field ϕ as $m_\chi^2 = m_\chi^2(0)+g^2\phi^2$ as seen in (1), pairs of particle-antiparticle of χ would be produced. The actual numerical results shown in Figure 2 support asymmetric production through the non-perturbative process in a case where the model has CP-violating parameters.

ASYMMETRIC PRODUCTION DUE TO OSCILLATING HIGGS BACKGROUND

As an application of asymmetric production to a realistic situation, it is interesting to consider a Type-I seesaw model that consists of the Standard Model and right-handed neutrinos. In a case where the Higgs background oscillates at a high energy scale, the non-perturbative particle production with a lepton number violating process would occur. Moreover, if the mass scale of the right-handed neutrino is much heavier than the Higgs oscillation scale, the asymmetric production of left-handed neutrinos might occur. Recently our study [11] has shown the possibility of such a scenario. With appropriate parameters, it is possible to explain the baryon asymmetry in the current Universe. The numerical results are shown in Figure 3. One can see that the net lepton number flips when the Higgs background reaches the edge of its oscillation. In the last stage of this dynamics, the Higgs shrinks rapidly at a certain moment because the gauge bosons are also exponentially produced due to the Higgs oscillation. The production of the gauge bosons also stops at a certain moment because their plasma affects the effective mass of the Higgs, and it spoils the motion of the Higgs. Finally, the whole state is fixed, and hence, the lepton-to-entropy ratio is also fixed.

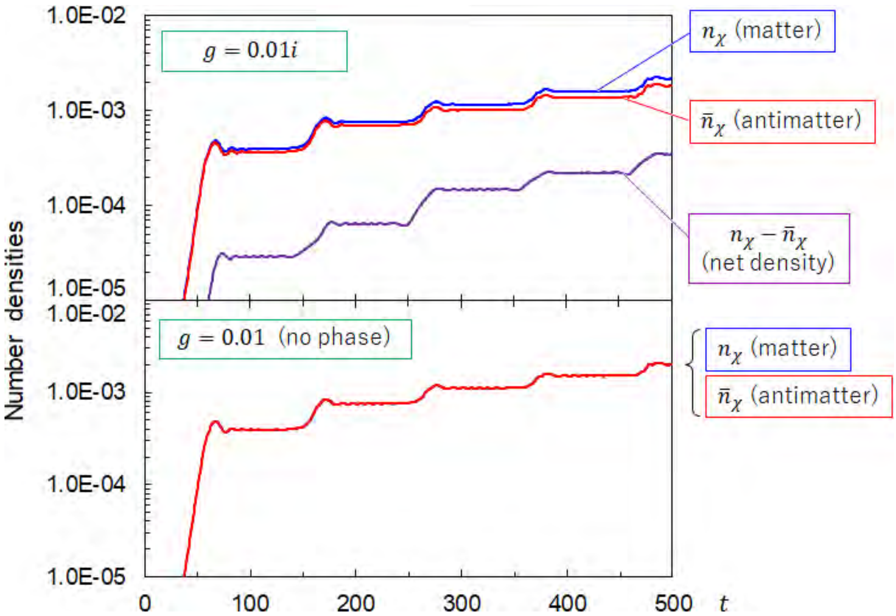

Fig. 2: The time evolution of each density. We chose the parameters as $m^2 = 0.15^2 + 4\cos^2 0.03t$, $m_\eta^2 = 0.1^2$, and $\epsilon = 10^{-4}$. The upper panel relates to a CP-violating interaction, and the lower panel relates to a CP conserving interaction.

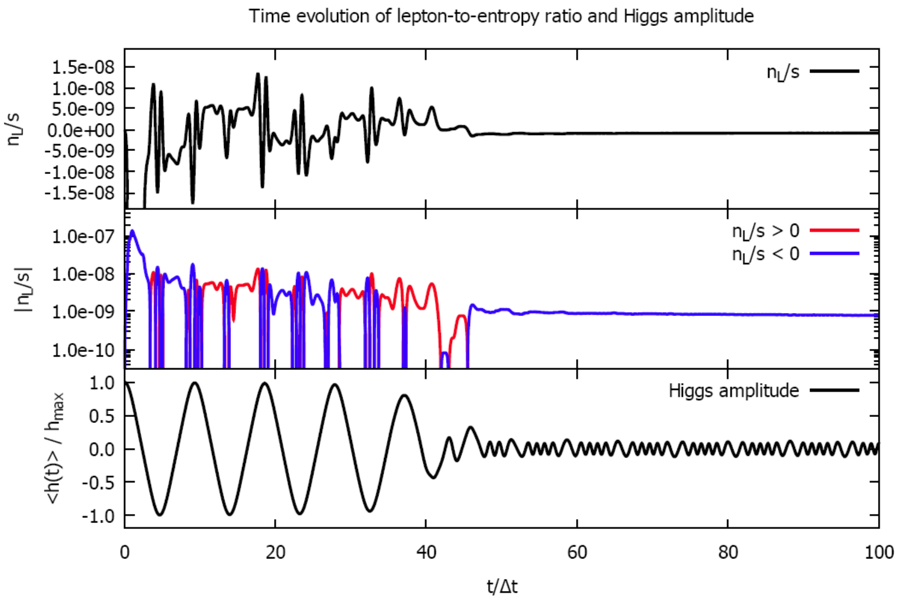

Fig. 3: The time evolution of the lepton-to-entropy ratio, its absolute value with the logarithmic scale and the amplitude of the Higgs background. To perform the calculation, the parameters are set by $\langle h(t_0)\rangle = 1.5 \times 10^{14}$ GeV and the mass scale of the lightest right-handed neutrino $M_1 = 10^{15}$ GeV. (There are other parameters. See [11] for details.) Δt is a time scale for particle production, which is estimated by $\Delta t \sim [0.1\langle h_{max}\rangle]^{-1}$ in this parameter set. The final value of the lepton-to-entropy ratio at $t/\Delta t = 100$ is $n_L/s = -6.54 \times 10^{-10}$.

Although the numerical behavior has been shown, it is hard to obtain analytic results because of the difficulty of the analysis of the non-perturbative process. Moreover, our evaluation has not included the expansion effects in the numerical calculation. Although there exist many hurdles to obtaining a complete understanding of the non-perturbative process, we hope these problems could be solved in the future.

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