

Reheat Temperature and the Right-handed Neutrino Mass

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We discuss the reheating temperature in the instant preheating scenario. In this scenario, at the last stage of inflation, the inflaton field first decays into another scalar field with an enormous number density via the instant preheating mechanism. Subsequently, the produced scalar field decays into normal matter accompanied by the usual reheating mechanism. As an inflationary model, we identify the inflaton as a field which gives rise to a mass for the right-handed (s)neutrino. One of the interesting consequences of the instant preheating mechanism is the fact that the reheating temperature is proportional to the mass of the decayed particle, *the right-handed sneutrino*, $T_R \propto M_R$. This is very different from the ordinary perturbative reheating scenario in which the reheating temperature is proportional to the mass of the inflaton.

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Inflation is a well-motivated scenario for solving many problems in the standard Big Bang cosmology: the flatness problem, monopole problem and so on [1]. The basic framework is constructed by using a single scalar field with a monomial potential. Although such a simple ‘toy’ model may be attractive, it has serious difficulties from the particle physics point of view. This is the so called gauge hierarchy problem in the standard model: When we take into account the radiative corrections of the scalar mass, it receives quadratically divergent contributions from UV physics. The most promising way to solve the gauge hierarchy problem is to introduce supersymmetry (SUSY) [2]. In models with SUSY it also gives a basic tool for constructing inflationary potentials in a rather natural way, rather than non-SUSY models, due to the enhanced symmetry and the fact that radiative corrections can be kept under control. In making an inflationary model in the non-SUSY set up we put a scalar field in by hand; however, in SUSY models we are fortunate to have many candidates for such scalar fields representing flat directions in the field configuration space. Indeed, there are many flat directions even in the MSSM [3].

From the low energy phenomenological point of view, supersymmetric grand unified theory (GUT) provides an attractive framework for the understanding of low-energy physics. In fact, for instance, the anomaly cancellation between the several matter multiplets present is automatic in GUT, since the matter multiplets are unified into a few multiplets, and the experimental data supports the fact of unification of three gauge couplings at the GUT scale, $M_{\text{GUT}} = 2 \times 10^{16}$ GeV, assuming the particle content of the minimal supersymmetric standard

model (MSSM) [4, 5]. The right-handed neutrino, which appears naturally in the SO(10) GUT, provides a natural explanation for the smallness of the neutrino masses through the see-saw mechanism [6].

However, there is no clear connection between the reheating temperature and GUT scale physics, like for the masses of the right-handed neutrinos. Hence, we shall discuss the reheating process using the instant preheating mechanism and show that the reheating temperature is given by a mass of the right-handed (s)neutrino.

Consider first, the following superpotential relevant for inflation [7]

$$W = M_I I^2 + M_{R_i} N_i^c N_i^c + \lambda_i I N_i^c N_i^c + Y_\nu^{ij} N_i^c L_j H_u, \quad (1)$$

where N_i^c and L_j are the right-handed neutrino and lepton doublet superfields and I is a complete Standard Model singlet superfield; later the scalar component of the singlet will be identified with the inflaton field.

From the superpotential (1), we obtain the Lagrangian relevant for the preheating as follows:

$$\mathcal{L} = -\frac{1}{2} M_I^2 I^2 - \frac{1}{2} M_{R_i}^2 \widetilde{N}_i^c{}^2 - \lambda_i^2 I^2 \widetilde{N}_i^c{}^2 + Y_\nu^{ij} \widetilde{N}_i^c L_j \widetilde{H}_u. \quad (2)$$

In such a model the *right-handed sneutrino* is coupled to the inflaton, and after developing a VEV the right-handed neutrinos obtain their masses at the order of about 10^{13} [GeV]. Furthermore, because $Y_\nu \sim Y_u$ (Y_u : up-type quark Yukawa coupling) is naturally expected in models with an underlying $SU(4) \subset SO(10)$ *Pati-Salam* symmetry; hence, we can naturally expect there to be many large couplings between the scalar field \widetilde{N}_i^c and the fermionic fields L_j and \widetilde{H}_u , which are required in order to obtain a viable instant preheating: $I \rightarrow \widetilde{N}_i^c \rightarrow L_j \widetilde{H}_u$.

First, let us briefly consider the perturbative treatment of reheating. When the inflaton potential is given as above the inflaton decay rate is found to be

$$\Gamma(I \rightarrow N_i^c N_i^c) \simeq \frac{|\lambda_i|^2}{4\pi} M_I \quad (3)$$

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and thus, within the perturbative treatment of reheating, the reheating temperature is obtained in terms of the decay rate as

$$T_R = \left(\frac{45}{2\pi^2 g_*} \right)^{1/4} (\Gamma M_{\text{PL}})^{1/2} \simeq 0.1 \times |\lambda_i| \sqrt{M_I \cdot M_{\text{PL}}} \\ \simeq 1.3 \times 10^{15} \text{ GeV} \quad (\text{for } |\lambda_i| \sim 1). \quad (4)$$

Here the mass of the inflaton, M_I , has been determined from the CMB anisotropy constraint,

$$\frac{\delta\rho}{\rho} = N \sqrt{\frac{4}{3\pi}} \frac{M_I}{M_{\text{PL}}} = 5 \times 10^{-5} \Rightarrow M_I \simeq 1.4 \times 10^{13} \text{ GeV}, \quad (5)$$

where we have taken the number of e-foldings to be $N \approx 60$. In the chaotic inflation scenario, the value of the inflaton at the time of terminating inflation is given by $I_{\text{end}} = M_{\text{PL}}/(2\sqrt{\pi})$, and the corresponding energy density is therefore

$$\rho_{\text{end}} = \frac{3}{2} V(I_{\text{end}}) = \frac{3M_I^2 M_{\text{PL}}^2}{16\pi} = (6.5 \times 10^{15} \text{ GeV})^4. \quad (6)$$

Let us now return to non-perturbative reheating, i.e. *preheating*. During reheating there are in general three time scales:

$$\left. \begin{aligned} t_{\text{osc}} &\sim M_I^{-1} \sim 10^{-36} s \\ t_{\text{exp}} &\gtrsim H_{\text{end}}^{-1} \sim 10^{-35} s \\ t_{\text{dec}} &\sim \Gamma_I^{-1} \sim 10^{-25} s \end{aligned} \right\} \Rightarrow t_{\text{osc}} \ll t_{\text{exp}} \ll t_{\text{dec}} \quad (7)$$

and so we expect several oscillations per Hubble time. Therefore, we would expect many oscillations of the inflaton field before it decays, which in general leads to broad parametric resonance [8]. In the usual broad parametric resonance for a hyperbolic potential, it is assumed that there is a succession of *scatterings* by the potential every time the field oscillates about the origin. However, there are cases when the field only needs to oscillate about the origin once (before rolling back down the potential again it decays into other particles by the standard reheating mechanism). This model is known as *instant preheating* [9], which in many ways is far simpler than general parametric resonance theory. Indeed, as mentioned in [9] under certain conditions one does not even need a parabolic potential, provided that the inflaton is coupled to another field quadratically. Also, recently, it has been pointed out in [10] that the thermalization process is very slow in SUSY models due to the presence of flat directions in the SUSY potential. However, in this letter, we adopt a model where the thermalization process occurs quickly by taking a suitable choice of parameters in the model.

Given any inflationary models, we would like to investigate the effects of preheating to generate a large decay rate for the inflaton. This can be achieved by using the instant preheating mechanism [9]. Thus, if the inflaton oscillates about the minimum of the potential only once

it is possible to show that, see [8, 9],

$$n_k = \exp\left(-\frac{\pi(k^2/a^2 + M_{R_i}^2)}{\lambda_i M_{R_i} \langle \mathcal{I} \rangle}\right) \quad (8)$$

and as discussed in [9] $M_{R_i} \langle \mathcal{I} \rangle$ can be replaced by $|\dot{\mathcal{I}}|$ which leads to

$$n_k = \exp\left(-\frac{\pi(k^2/a^2 + M_{R_i}^2)}{\lambda_i |\dot{\mathcal{I}}|}\right). \quad (9)$$

This can then be integrated to give the number density for the right-handed sneutrinos, \widetilde{N}_i^c ,

$$n_{\widetilde{N}_i^c} = \frac{1}{2\pi^2} \int_0^\infty dk k^2 n_k = \frac{(\lambda_i \dot{\mathcal{I}})^{3/2}}{8\pi^3} \exp\left(-\frac{\pi M_{R_i}^2}{\lambda_i |\dot{\mathcal{I}}|}\right) \\ = \frac{(M_{R_i} \lambda_i \langle \mathcal{I} \rangle)^{3/2}}{8\pi^3} e^{-\frac{\pi M_{R_i}}{\lambda_i \langle \mathcal{I} \rangle}} \simeq \frac{M_{R_i}^3}{8\pi^3} e^{-\pi}. \quad (10)$$

As argued in [9], if the couplings are of order $\lambda_i \sim 1$ then there need not be an exponential suppression of the number density. This fact has recently been used in an interesting model of non-thermal leptogenesis in [11]. The resultant reheating temperature from instant preheating is given by

$$T_R = \left(\frac{30}{g_* \pi^2} \cdot m_{\widetilde{N}_i^c} \cdot n_{\widetilde{N}_i^c} \right)^{1/4} \simeq \left(\frac{15}{4\pi^5 g_*} \right)^{1/4} M_{R_i} e^{-\pi/4} \\ \cong 0.05 \times M_{R_i}. \quad (11)$$

It should be stressed that the reheating temperature in equation (11), obtained from the preheating mechanism, is proportional to the mass of the decayed particle, *the right-handed sneutrino*, i.e. $T_R \propto M_R$, and does not depend on the inflaton mass. This is very different from the ordinary perturbative reheating scenario in which the reheating temperature is proportional to the mass of the inflaton field, see Eq. (4). This characteristic of proportionality is applicable to all the models using preheating. A nice example is in the next to minimal supersymmetric standard model (NMSSM) [12], where we can identify a singlet in this model as the inflaton [13]. In such a case, very interestingly, the reheating temperature is determined by the Higgs mass: $T_R \propto m_H$.

To summarise, in this letter we have discussed the connection between the reheating temperature and the masses of the right-handed (s)neutrinos. The reheating process has been described as follows: At the last stage of inflation, the inflaton field first decays into another scalar field with an enormous number density, via the instant preheating mechanism. Subsequently, the produced scalar field decays into normal matter accompanied by the usual reheating mechanism. Interestingly, the reheating temperature is proportional to the mass of the decayed particle, *the right-handed sneutrino*. We emphasise that this is very different from the ordinary perturbative reheating scenario in which the reheating temperature is proportional to the mass of the inflaton.

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