PROCEEDINGS OF SCIENCE

Direct leptogenesis*

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It is pointed out that lepton asymmetry can be generated through CP-preserving inflaton decay into Higgs boson when the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix has a proper CP phase. The leptons produced during thermalization process undergo flavor oscillations where CP violation takes place. The $llHH$ terms relevant to the active neutrino masses give lepton number violations. Our scenario can be tested from the ground-based neutrino experiment.

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1. Introduction

The origin of the baryon asymmetry is a long-standing puzzle in the Standard Model (SM) and the Standard Cosmology. The successful generation of the baryon asymmetry requires the process satisfying the Sakharov's conditions: **1.** the breaking of the baryon/lepton number, **2.** the breaking of the C and CP symmetry, and **3.** the deviation from the thermal equilibrium. It was known that it is difficult to generate the baryon asymmetry within the SM and standard cosmology.

Recently it was discovered that the SM neutrinos oscillate. This phenomenon clearly is a new physics beyond the SM, because the SM predicts massless neutrinos. To explain the neutrino oscillation, it may be simple to assume the SM is an effective theory whose Lagrangian is with various higher dimensional operators. Then the total Lagrangian is given by

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{\kappa_{ij}}{2}(\bar{l}_i^c P_L l_j)HH + \text{h.c.} + ... \tag{1.1}$$

where $\mathscr{L}_{\rm SM}$is the SM Lagrangian, H, l are SM Higgs and left-handed lepton fields, and ... denotes the $d > 5$ operators. Through the $llHH$ term, the neutrinos get masses and can oscillate. The $llHH$ term could arise, for example, by integrating out right-handed neutrinos [3, 4][1], but we do not specify the UV model and we neglect the terms of ... in the following discussion.

The $llHH$ term obviously breaks the lepton number and, moreover, could lead to CP violation, which may be already observed in the neutrino oscillation experiments (e.g. Ref. [2]). Thus the conditions, **1.** and **2.**, are satisfied. Moreover, **3**. is satisfied if one supposes inflationary cosmology. Since during the inflation the Universe is cold, there is a process of thermalization during which the Universe becomes hot and the SM particles get into thermal equilibrium. This is obviously an out of equilibrium process. We will encounter two kinds of thermalization process depending on the temperature. One is the reheating era of the Universe, which is driven by the decay of the inflaton, which corresponds to the highest temperature, T_R, of the radiation dominant era. This era exists in general. When $T_R \gtrsim 10^{14}\,$GeV, there is another era out of equilibrium due to the decoupling of the gauge interaction. This is because the interaction rate is roughly given by $\Gamma_{\rm th} \sim \alpha_i^2 T$ where α_i denotes the fine structure constant for the gauge fields, while the Hubble expansion rate is $H \sim \frac{T^2}{M_{\rm pl}}$. Thus, for certain high temperature $T \gtrsim 10^{14}\,$GeV, $\Gamma_{\rm th} < H$ and the gauge forces are no more important. Consequently, for $T \gtrsim 10^{14}\,$GeV, most of the SM particles are decoupled and around $T \sim 10^{14}\,$GeV, they are thermalized due to the gauge interactions.

To sum up, if we consider eq.(1.1) to explain the neutrino oscillation, during the thermalization era, all the three conditions of Sakharov are satisfied and thus baryon asymmetry may be generated. In the following sections, we will see indeed the baryon asymmetry is generated.

2. Mechanism for leptogenesis and a numerical result

During thermalization, the isolated particles are scattered with and into thermal plasma. Before the scattering, a particle follows the Schrödinger equation for a free particle, and it is "observed" through the scattering by the ambient plasma. For instance, a neutrino undergoes neutrino flavor

[1] Recently, It was shown that the charge quantization may be related with the $llHH$ term due to supersymmetry at the Planck-scale [5].

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oscillation during the thermalization before it is scattered by the thermal plasma. Notice that at the early and dense Universe, although the Higgs field does not have expectation value, neutrinos get thermal masses through matter effect just like the neutrinos in the sun. It was first pointed out by Y. Hamada and R. Kitano [6], that due to the neutrino oscillation during the reheating era, there can be CP violation and the CP violation can lead to baryon asymmetry of the Universe by using the Lagrangian (1.1) plus a dimension eight term.

Here, we use the kinetic equations which can describes the quantum effect during the thermalization and can be derived from the first principle of the Lagrangian, to show that the baryon asymmetry can be generated with eq. (1.1) during thermalization era. The equations are

$$i\frac{d\rho(\mathbf{p})}{dt} = [\Omega(\mathbf{p}), \rho(\mathbf{p})] + ..., \quad i\frac{d\bar{\rho}(\mathbf{p})}{dt} = -[\Omega(\mathbf{p}), \bar{\rho}(\mathbf{p})] + ... \tag{2.1}$$

respectively, for the 3×3 density matrix of l, $\rho(\mathbf{p})$, and $\bar{l}$, $\bar{\rho}(\mathbf{p})$ [7, 1]. Here flavor indices are implicit. The first term represents the oscillation where the thermal mass for the leptons is included, while the terms in ... correspond to the destruction and production processes. The sign of the oscillation terms is opposite between the leptons and anti-leptons, which is the only difference between the two equations. This difference serves as the "strong phase" in the CP violation. Therefore ρ and $\bar{\rho}$ develops differently when the first term is non-vanishing. Although are proportional to the unit matrix at thermal equilibrium, ρ and $\bar{\rho}$ can have flavor dependence during the thermalization in general. This is because the initial condition (from inflaton decay) may not be flavor blind, and also the Yukawa and $llHH$ interactions relevant for thermalization have flavor-dependence. In particular, if the PNMS matrix has CP phases, the difference leads to flavor dependent lepton asymmetry during the thermalization.

The $llHH$ term provides washout effect, which decreases or increases the total lepton asymmetry. Notice that this effect is also flavor dependent. For instance, with one massless neutrino (at the vacuum), the corresponding $llHH$ term is vanishing which, of course, does not provide the washout effect for the relevant flavor. Alternatively, with degenerate neutrino masses, $llHH$ term enjoys an $O(3)$ flavor symmetry, and the flavor dependent asymmetry corresponds to the generators are conserved. Therefore, when the temperature is sufficiently high, the flavor-dependent asymmetry created by the oscillation partially remains. As a result, the net lepton asymmetry can be created. This is the basic mechanism of our scenario.

By solving the kinetic equation with several approximations, we show numerically that our mechanism works. We focus on one scenario in Ref.[1] where the inflaton ϕ dominantly decays into the Higgs boson which could be due to the renormalizable coupling of $\mathscr{L} \supset A\phi\,|H|^2$. The Higgs bosons from the decay scatter with each other via the SM couplings and $llHH$ interaction. The SM particles, including the leptons, are copiously produced through the scattering. The density matrices of produced leptons are flavor dependent and not proportional to the unit matrix. These leptons also scatter with the ambient particles and are gradually thermalized.

A numerical result for lepton asymmetry is shown in the left panel of Fig. 1, where we find enough amount of the asymmetry is generated depending on κ_{ij} and inflaton mass m_ϕ and T_R. In particular, when $T_R \gtrsim 10^{14}$ GeV, the flavor oscillation contribution is most significant at $T \simeq 10^{14}$ GeV which is cutoff due to the thermalization via gauge interaction. (See Ref. [1] for more detail.) Thus the region with $T_R \gtrsim 10^{14}$ GeV does not depend much on T_R and m_ϕ and the prediction

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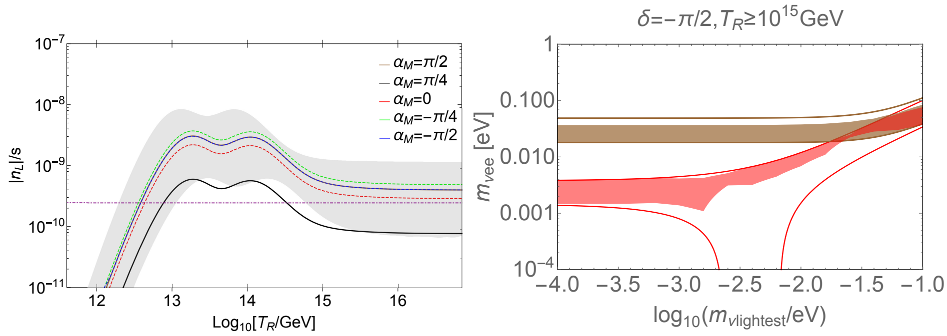

Fig. 1: The dependence of lepton asymmetry on T_R with different Majorana phase α_M with dirac phase $\delta = -\pi/2$, for inverted mass hierarchy with $m_\phi/T_R = 100$ and $m_{\nu\mathrm{lightest}} = 0$ eV. (Left) The shaded regions denote the uncertainty for $\delta = -\pi/2, \alpha_M = 0$ for comparison. The solid and dashed lines denote the sign of the asymmetry is minus and plus, respectively (the required asymmetry is minus). The value of effective neutrino Majorana mass, $m_{\nu ee}$, compatible with our scenario for $T_R \geq 10^{15}$ GeV, $\delta = -\pi/2$ (right). The region between upper and lower black (brown) lines is the general possibility for normal (inverted) hierarchy while the shaded regions are our prediction.

almost relies on the parameter of PNMS matrix and the neutrino mass hierarchy. It is interesting that the UV independent value is consistent with the observed baryon asymmetry. We also show in the right panel the effective neutrino mass $m_{\nu ee}$, which is relevant to the neutrinoless double beta decay. For other parameter choices and dependences, see Ref. [1].

We have discussed the case with the inflaton dominantly decays to the Higgs boson. If the inflaton perturbatively decays also to lepton with flavor violation, the lepton asymmetry needs $T_R \gtrsim 10^8$ GeV [1], which can be even smaller for non-perturbative reheating. (See e.g. Refs. [8].)[2]

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