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Baryogenesis via neutrino oscillation magic*

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I show that matter-antimatter asymmetry can be generated through the neutrino oscillation at the very beginning of the Universe. The neutrino oscillation happens due to the matter effect despite the tiny vacuum mass of the neutrino in the presence of the dimension-five term contributing to the ordinary Majorana neutrino mass.

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1. Introduction

The origin of the matter-antimatter (baryon) asymmetry is a long-standing puzzle in the Standard Model (SM) in inflationary cosmology. The successful generation of the baryon asymmetry requires the process satisfying the Sakharov's conditions: **1.** the interaction violating the baryon number, **2.** the breaking of the C and CP symmetry, and **3.** the out of equilibrium of the interaction **1**. It was known that it is difficult to generate the baryon asymmetry within the SM and standard cosmology. So we need new physics to explain the baryon asymmetry.

A clear new physics is the neutrino oscillation, which means neutrinos have masses. To explain the neutrino oscillation, one of the simplest way is that the SM is an effective theory whose Lagrangian is with various higher dimensional operators. Then the total Lagrangian is in general given by

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

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]. (See also Ref. [5].)[1]. It may also just exist and becomes strong at a high energy scale. We do not specify the UV model and we neglect the last terms $(\cdots)$ in the following discussion.

The $LLHH$ term obviously violates the baryon minus lepton (B-L) number. Within the SM there is a sphaleron effect which violates the baryon plus lepton (B+L) number, but conserves the B-L number. The effect gives non-vanishing baryon asymmetry if $B-L$ number is generated, i.e. the generated lepton number via $LLHH$ interaction can be transferred into the baryon number through the sphaleron process. The baryogenesis via this kind of asymmetry transferring is called leptogenesis [7]. Therefore, due to the interaction of the $LLHH$ we could have leptogenesis if **2** and **3** are satisfied.

The CP violation happens due to neutrino oscillation if there is certain CP phases in the κ_{ij}. In fact the CP violation is favored in some neutrino oscillation experiments (e.g. Ref. [8]). Thus the conditions, **1.** and **2.**, are satisfied. Moreover, **3**. is satisfied in 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. The thermalization process is a one-way process, which is a very good environment of the baryogenesis.

We will consider the neutrino oscillation during the thermalization epoch with the $LLHH$ term and show that the baryon asymmetry can be generated. In particular, if the inflaton decays into the Higgs bosons, the baryon asymmetry can be related with the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. Thus our scenario can be tested from the ground-based experiments for neutrinos.

[1] It was shown that one of the neutrino oscillation scales can be obtained in the supersymmetry broken at the Planck-scale if wino is anomaly induced [6]. In the scenario the charge assignment of the SM particle contents are predicted from anomaly-cancellation since the Higgs boson is identified as a slepton.

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2. Mechanism for leptogenesis

Let us consider inflaton decays. Suppose the inflaton decays to left-handed leptons (neutrinos).

$$\phi \to L_\phi + X, \quad \bar{L}_\phi + \bar{X}. \tag{2.1}$$

Here X are arbitrary final states which is not relevant. The final lepton state, L_ϕ, is a linear combination of L_e, L_μ, and L_τ in general. Through the decay the Universe is reheated to the temperature, $T = T_R \simeq (g_* \pi^2/90)^{-1/4}\sqrt{\Gamma M_{\rm pl}}$, with the total decay rate Γ, the effective relative degrees of freedom $g_* \simeq 106.75$, and the reduced Planck mass $M_{\rm pl} \simeq 2.4 \times 10^{18}$ GeV.

At the moment of the inflaton decay $t = t_R \simeq 1/\Gamma$ at the reheating, there are two components in the Universe. One is the plasma which is generated at $t \ll t_R$. The plasma is soon thermalized due to the fast interaction via the gauge. This is characterized by the temperature T_R, which should satisfy

$$T_R \leq m_\phi \tag{2.2}$$

for the perturbative decays of the inflaton. Another component is the direct decay product at $t = t_R$. The lepton in the decay product is generally out of equilibrium. The energy of the lepton is around m_ϕ. The lepton will be thermalized promptly due to the interaction with the thermal plasma. We will focus on the thermalization of the lepton at $t \simeq t_R$. We will not consider $t \ll t_R$, because the baryon asymmetry generated at the time scale is diluted due to the inflaton decays.

The lepton asymmetry Δ_L is produced in the following way. At $t = t_R$, the lepton of momentum $\mathbf{p}$ produced by an inflaton decay, L_ϕ, is represented as a quantum state

$$|L_\phi, t_R\rangle, \tag{2.3}$$

which evolves as

$$|L_\phi, t\rangle = \sum_i c_i \exp\left[-i\int_{t_R}^{t} E_i dt'\right]|i\rangle \tag{2.4}$$

where $|i\rangle$ is the flavor eigenstate of the left-handed leptons, $i = e, \mu, \tau$, with momentum $|\mathbf{p}| \sim m_\phi$. We have defined

$$c_i \equiv \langle i|L_\phi, t_R\rangle. \tag{2.5}$$

For $|\mathbf{p}| \gtrsim T$, the dispersion relation becomes flavor dependent such as

$$E_i \simeq y_i^2 \frac{T^2}{16|\mathbf{p}|} + \cdots, \quad (i = e, \mu, \tau), \tag{2.6}$$

where y_i are the Yukawa coupling constant for the charged leptons, $y_i = m_i/\langle H\rangle$. The oscillation effect of the left-handed leptons via the thermal mass in the context of the leptogenesis is first pointed out in Ref. [9]. We assumed $y_\tau \gg y_N$, and '$\cdots$' contains the flavor-blind terms irrelevant for the flavor oscillation. This is nothing but the matter effect thanks to the preexisting thermal plasma. This plasma also prevents the flavor oscillation from lasting too long. The oscillation is terminated when the leptons annihilate with the plasma. The free propagation time scale, $t_{\rm MFP}$, is given as,

$$t_{\rm MFP} \simeq \Gamma_{\rm th}^{-1} \simeq \left(\alpha_2^2 T\sqrt{\frac{T}{|\mathbf{p}|}}\right)^{-1}. \tag{2.7}$$

where we have taken into account the Landau-Pomeranchuk-Migdal (LPM) effects [10, 11, 12] for estimating the energy loss process important for the thermalization. Therefore, the quantum state of the leptons shortly after the time scale, $t_{\rm MFP}$, is given by

$$|L_\phi, t_R + t_{\rm MFP}\rangle \simeq \sum_i c_i \left(1 - i\frac{y_i^2}{16\alpha_2^2} + ..\right)|i\rangle. \quad (2.8)$$

Here, the scattering takes several times and the energy of the lepton becomes smaller gradually, and thus the oscillation phases are calculated when $|\mathbf{p}| \sim T_R$, where the oscillation is terminated due to the pair annihilation of the leptons. The evolution of each flavor component differs by a phase, and for τ the difference is

$$\frac{y_\tau^2}{16\alpha_2^2} \sim 0.005. \quad (2.9)$$

Notice that this phase is the so-called CP-even phase which is important for the CP violation in neutrino oscillation. In fact, the CP violation probability is given by

$$P = \left(|\langle L_I|L_\phi, t_R + t_{\rm MFP}\rangle|^2 - |\langle \overline{L_I}|\overline{L}_\phi, t_R + t_{\rm MFP}\rangle|^2\right). \quad (2.10)$$

where $\langle L_I|$ is the state that the flavor is observed which is defined soon. We obtain

$$P \propto \frac{y_\tau^2}{16\alpha_2^2} \quad (2.11)$$

Thus, the 0.005 value can be the origin of the baryon asymmetry $\mathcal{O}(10^{-10})$.

The next question is how the flavor is observed. To observe the flavor we need flavor-dependent interaction process. There are two processes that are not flavor-blind: the scatterings via the lepton Yukawa interactions and via the $LLHH$ interactions. The state of $\langle L_I|$ is defined so that the interaction basis is diagonalized. The important thing is that once the neutrino flavor is observed via the $LLHH$ interaction, the anti-neutrino is produced. Since all of the three conditions of Sakharov's are satisfied during the period of thermalization, the baryon asymmetry can be generated. The naïve estimation can be made on rate of the asymmetry of lepton to the entropy density as

$$\frac{\Delta n_L}{s} \propto B_{\phi\to\nu_{\rm ini}+X/\overline{\nu_{\rm ini}}+\overline{X}} \times t_{MFP}\frac{\Delta E_i^2}{T} \times \frac{\sigma^{\rm th}_{LLHH}}{\sigma^{\rm th}_{\rm yukawa}}, \quad (2.12)$$

Here, the right-handed side denotes the product of branching ratio, oscillating phase, and the ratio of the scattering cross section via the $LLHH$ interaction to Yukawa interaction, which represent, respectively, how frequently the inflaton decays to lepton (neutrino), the CP violation happens, and lepton number violation happens. The left hand side becomes comparable to the right hand side when $T_R \simeq m_\phi$, and there is general flavor structure with $\mathcal{O}(1)$ CP phases. This reduces to

$$\frac{\Delta n_L}{s} \propto B_{\phi\to\nu_{\rm ini}+X/\bar{\nu}_{\rm ini}+\bar{X}} \times 10^{-9}\left(\frac{T_R}{10^9 GeV}\right)^2, \quad (2.13)$$

which should be compared with the $|\Delta n_L/s| \sim 10^{-10}$ which typically explains the baryon asymmetry of our Universe via the sphaleron transition. Consequently, we find that the asymmetry of our Universe can be explained if $T_R \gtrsim 10^{8-9}$ GeV.

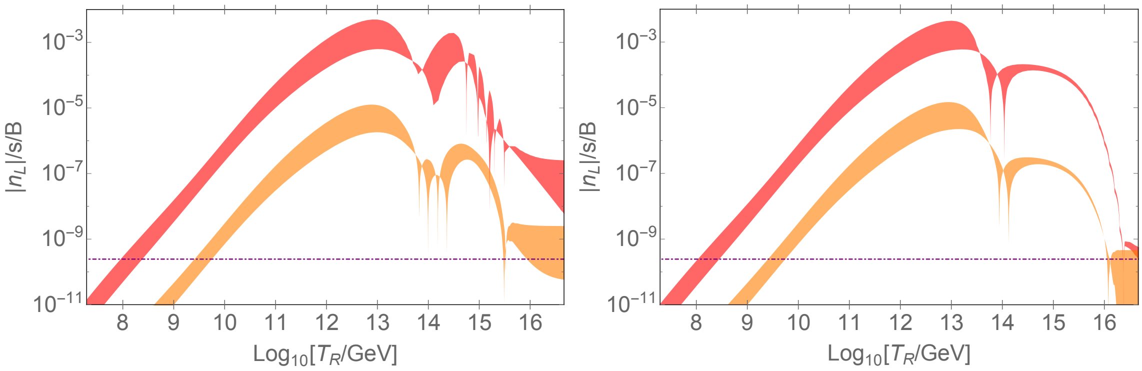

Fig. 1: The dependence of lepton asymmetry on the reheating temperature with $\alpha_M = 0.3\pi, \delta = -\pi/2$, $V = \frac{1}{\sqrt{3}}(1,1,1)$ with the normal (inverted) mass hierarchy with one massless neutrino, $m_{\nu\text{lightest}} = 0$ eV, in the left (right) panel. The red and orange bounds represent $m_\phi/T = 1$ and 100, respectively. Each band corresponds to the variance of $C = C'$ between $1/3$ and 3. The purple line represents the required lepton asymmetry.

We have solved the kinetic equation [13] with certain approximations [1] to numerically confirm the previous naive discussion. The result is given in Fig. 1 for normal and inverted hierarchy. For detail see [1]. One can find that when $T_R \gtrsim 10^8$GeV the enough baryon asymmetry can be generated. We notice that even at very high temperature the asymmetry is not vanishing due to the washout effect. This is due to the approximate symmetry during the temperature range. At the high temperature, the Yukawa interactions are not important, but the $LLHH$ interactions get important. Since $LLHH$ coupling, κ, respects symmetry depending on the neutrino mass structure, the asymmetry is not completely washed out at the high temperature. For instance, at the normal hierarchy, we have a $\mathrm{U}(1)$ symmetry corresponding to a massless neutrino. This means that there can be a non-vanishing chemical potential. As a result the lepton asymmetry is not completely washed out. For the inverted hierarchy, the $\mathscr{O}(2)$ symmetry rotating the degenerated two neutrinos allows the non-vanishing chemical potential.

3. Baryogenesis with PNMS matrix

Our scenario depends on how inflaton produces the neutrinos. In this sense, the scenario is UV-dependent. Here we assume that the inflaton couples to the SM particles dominantly with renormalizable interaction terms. The only allowed ones are

$$\mathscr{L} \supset -A\phi|H|^2 - \lambda_\phi \phi^2 |H|^2 \tag{3.1}$$

where A and λ_ϕ are real parameters since inflaton ϕ is a real field. Although the inflaton does not directly couple to the leptons, the Higgs fields from the decays scatter with each other and form plasma soon. During the thermalization, we have the process,

$$HH \to \bar{L}_\alpha \bar{L}_\alpha \tag{3.2}$$

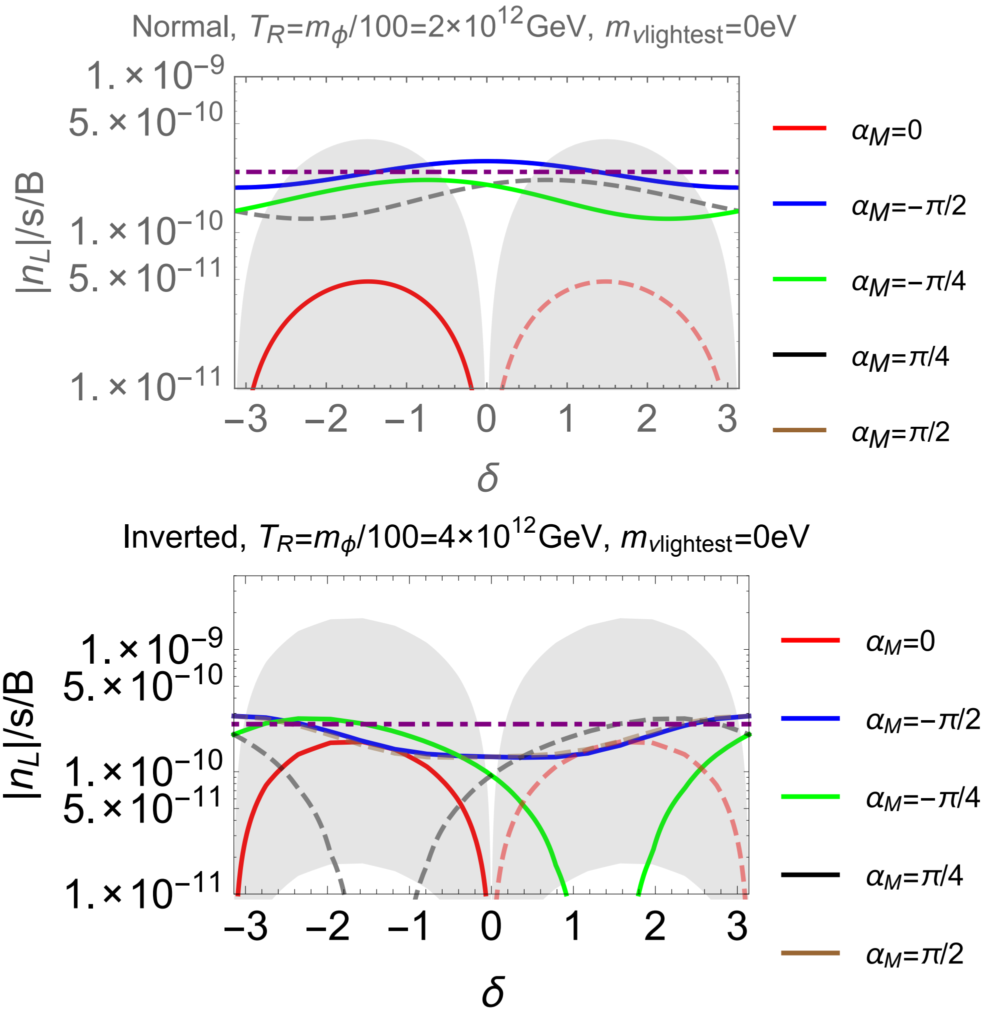

Fig. 2: Lepton asymmetry dependence on δ for inflaton decay dominantly to Higgs boson. The uncertainty for $\alpha_M = 0$ case is shown in the gray bands. The solid (pale dashed) lines represent that the predicted Universe is matter (antimatter) dominated. Thus the dashed lines are excluded. The purple line represents the required amount of the lepton asymmetry.

via the $LLHH$ interaction. The L_α undergoes flavor oscillation and so the baryon asymmetry can be generated as in the previous section. The important thing in this case is that the CP-phase can only appear in the neutrino sector, i.e. in the PNMS matrix. Therefore the resulting baryon asymmetry is a function of the CP phase in the PNMS matrix which means our scenario can be tested in the low energy experiments for neutrino. In Fig. 2, I show that the dependence on the Dirac and Majorana phases in normal and inverted hierarchies. We find that the sign of the asymmetry essentially depends on the phases, which implies our scenario is linked to the ground-based experiment. In particular, the prediction on the $m_{\nu ee}$ relevant to the neutrino-less double beta decay experiments are given in Fig. 3.

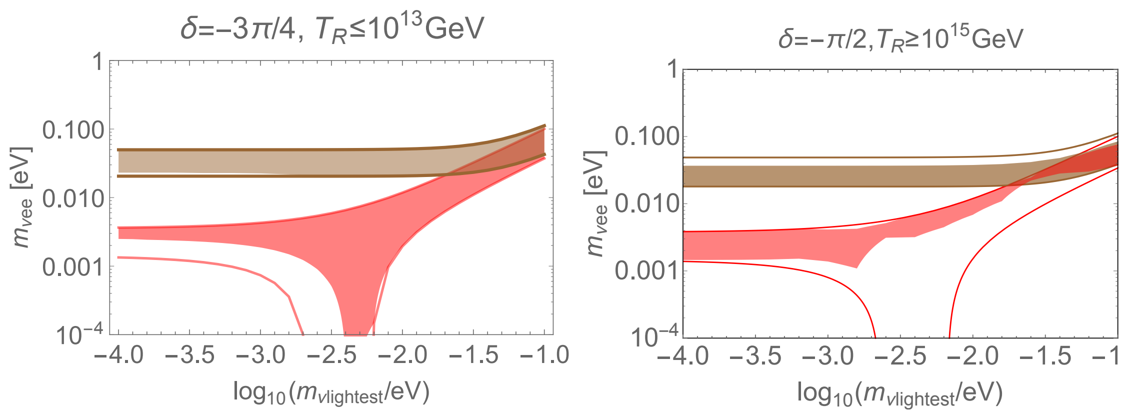

Fig. 3: The value of effective neutrino Majorana mass, $m_{\nu ee}$, compatible with our scenario. The inflaton decays into Higgs boson. $T_R \lesssim 10^{13}$ GeV, $\delta = -3\pi/4$ and $T_R \gtrsim 10^{15}$ GeV, $\delta = -\pi/2$ are assumed for the left panel and right panel, respectively. The region between upper and lower red (brown) lines is the general possibility for normal (inverted) hierarchy while the shaded regions are our prediction.

4. Conclusions and discussion

I have shown that the neutrino oscillation and matter-antimatter asymmetry of our Universe are tightly related. It was proposed that the left-handed neutrinos, generated from the inflaton decay, undergoes the CP-violating neutrino oscillation via the thermal mass, and then the lepton asymmetry is created via the scattering with thermal plasma. The mechanism works even within the SM plus the dimension-five Majorana mass term of the left-handed neutrino, i.e. without introducing a right-handed neutrino. In particular, the oscillating left-handed neutrinos can be produced through the scattering of the thermal plasma in the very early Universe, in which case the matter-antimatter asymmetry is a direct consequence of the neutrino oscillation, i.e. the CP violation for the asymmetry originates from the PMNS matrix. Therefore, the test of the neutrino oscillation in the ground-based experiment may be a direct probe of the origin of the matter-antimatter asymmetry.

We have shown that the matter-antimatter asymmetry of our Universe. If the inflaton perturbatively decays also to lepton with flavor violation, the lepton asymmetry needs $T_R \gtrsim 10^8$ GeV [1]. As recently shown in [2], if the reheating completes via the dissipation effect, where the scattering between the inflaton and the thermal plasma significantly generates the radiation, the reheating temperature can be even smaller. In particular, in the ALP inflation [14, 15, 16],[2] the reheating temperature can be as small as $T_R \gtrsim 10^6$ GeV for the correct baryon asymmetry. The required temperature can be reduced to $T_R \sim 10^4$ TeV($T_R \sim 100$ GeV) for the reheating via perturbative decays (dissipation effect) of inflaton if one introduces a single GeV scale right-handed neutrino.

Quark-flavor oscillations during the reheating epoch, on the other hand, are shown to be important for baryogenesis [24]. To have baryon number violation, one can introduce dimension-nine operators a la neutron-antineutrino oscillation operators, which stabilize the proton by a baryon parity. The sphaleron effect is not crucial to the mechanism and the reheating temperature can be

[2] In the low-scale ALP inflation, the abundance of the light scalar particles can be significantly altered due to the Bunch-Davies distribution formed during the inflation [17, 18, 19, 20, 21, 22, 23].

below the 100 GeV. The scenario can be searched for via neutron-antineutron oscillation experiments. The small reheating temperature can be consistent with various UV models.

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