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Type-II Leptogenesis

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We discuss our new theory on baryogenesis 'Type-II leptogenesis' [1] which is different from the well-known 'Type-I leptogenesis' [2]. First, we will briefly comment on the Jarlskog phases in the CKM and PMNS matrices, $\delta_{\rm CKM}$ and $\delta_{\rm PMNS}$. Then, the PMNS phase is used in the 'Type-II' leptogenesis for Sakharov's condition on the global quantum number generation in the Universe. For this to be effective, the SU(2)×U(1) gauge symmetry must be broken during the leptogenesis epoch.

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1. Introduction

In this talk, I discuss the mere 5 % of the energy pie (mainly of atoms composed of baryons) of the Universe. At the most fundamental level of the grand unification(GUT) scheme, it belongs to the problem on the chiral representation of quarks [3]. In cosmology, it belongs to Sakharov's three conditions. The first one is the existence of baryon number (B) violating interaction, and the second is the existence of CP violation [4]. For example, at the red clover point of Fig. 1 let us calculate baryons moving forward/backward in time. The ratio is the number of baryons over the number of antibaryons. Therefore, to have a nonzero ΔB, we need T or CP violation. We also need to break C. To see this, firstly assume T violation and calculate ΔB at the red clover point in Fig. 1. Second, integrate over solid angles. At the black clover point, if C is not broken then ΔB is minus that of red clover point, because $P=-1$ is multiplied. Then, integration over the solid angle gives $\Delta B=0$. Therefore, the needed T violation in the $\Delta B\neq 0$ processes must accompany the C violation also. The CP violation in the standard model(SM) arises as the "V-A" form and hence also breaks C. Sakharov's third condition on "out of thermal equilibrium" is satisfied by the decay of some heavy particle(s), which is usually assumed in most baryo- and lepto-genesis mechanisms.

The CP violation seems to work also in some models of dark matter in the Universe. The asymmetric dark matter scenario for this case follows the paradigm of baryogenesis and hence CP violation is the key here also. The axion scenario for dark matter [5] uses an oscillating axion field whose amplitude at present is of order $|\bar{\theta}_{\rm max}|\simeq 10^{-20}$ [6]. For nonzero $\bar{\theta}$ though oscillating, CP is violated and hence CP violation is the key in the axionic dark matter scenario also. Only, the WIMP scenario for dark matter uses just the cosmological freezeout temperature, not employing any kind of CP violation [5].

In this talk I will briefly review the weak CP violation first and then present a new mechanism on the leptogenesis that we call 'Type-II leptogenesis' with CP violation in the chiral theory [1].

2. CP violation, and CKM and PMNS matrices

In the SM, CP violation is represented by $W_\mu^\pm$ couplings to SU(2)$_W$ doublet fermions which are parametrized by the unitary CKM and PMNS matrices [7]. In particular, the elements of the CKM matrix are well-known by now, and there are three classes of parametrizations, which we explain below. Let the CP phase of the CKM matrix be $\delta_{\rm CKM}$. Then, any Jarlskog triangle has an angle

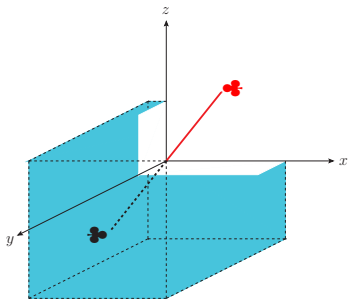

Figure 1: The B number in the parity operated part in the Universe.

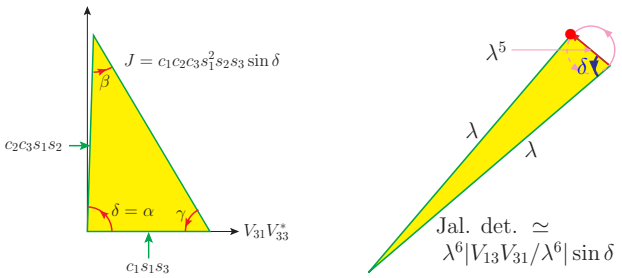

Figure 2: Two Jarlskog triangles of area $O(\lambda^6)$: (a) with three comparable sizes of $O(\lambda^3)$ in the KS parametrization [7], and (b) with two long sides of $O(\lambda)$. These two areas must be exactly the same. In (b), by roating the angle δ, J is found to be the maximum with $\delta\simeq 90^o$.

$\delta_{\rm CKM}$ [8]. The Jarlskog invariant J has a simple expression with Det. $V_{\rm CKM}=1$, $J=|{\rm Im}\, V_{31}V_{22}V_{13}|$ [8]. There are six Jarlskog triangles. A triangle with the lengths of $O(\lambda^3)$ for all three sides, where $\lambda=\sin\theta_C$, is shown in Fig. 2 (a). Here we denoted the sides in the Kim-Seo (KS) parametrization [7]. In this figure, there are three angles, α,β and γ, any of which is not small. We can use any of these as $\delta_{\rm CKM}$, which can be called, 'α-class', 'β-class', and 'γ-class', respectively. The KS parametrization and the Kobayashi-Maskawa parametrization belong to the α-class, and the Chau-Keung-Maiani (CKM) parametrization belongs to the γ-class [8]. Note that the unitarity triangle in the PDG book gives: $\alpha=\left(85.4^{+3.9}_{-3.8}\right)^o$, $\beta=\left(21.50^{+0.76}_{-0.74}\right)^o$, $\gamma=\left(68.0^{+8.0}_{-8.5}\right)^o$. Since α is close to 90^o, we use the KS parametrization [7], with which one can prove that the weak CP violation is maximal with the currently determined real CKM angles. Since any Jarlskog triangle gives the same J, consider the triangle with two long sides of $O(\lambda)$ as shown in Fig. 2 (b). The area of the triangle ($=\frac{1}{2}J$) is $O(\lambda^6)$. So, it is $\frac{1}{2}\lambda\cdot\lambda^5\cdot\sin\delta$ which is maximal with $\delta=90^o$. With the measured real angles $\theta_{1,2,3}$, this maximality must be true in any parametrization. For the CKM parametrization, it must be so but the proof may not be so simple[1] as given in the KS parametrization where $\delta_{\rm CKM}=\alpha$ is close to $\frac{\pi}{2}$. This is based on the fact that in a given parametrization all the six triangles give the identical area. Note, however, that at present a specific parametrization is not better than others. If one finds a process to determine three real angles or $\delta_{\rm CKM}$ itself, the measured value(s) for that process can choose a correct class of parametrization scheme. Thus, there is a possibility that $\delta_{\rm CKM}=\frac{\pi}{2}$.

It will be very interesting if the leptonic CP violation in the SM also gives $\delta_{\rm PMNS}=\pm\frac{\pi}{2}$. Then, one may look for a theory relating $\delta_{\rm CKM}$ and $\delta_{\rm PMNS}$ as tried in [9]. Even though the significance is very low, there is a hint that $\delta_{\rm PMNS}\approx-\frac{\pi}{2}$ [10]. But $\delta_{\rm PMNS}\neq 0$ is a more significant statement than fixing it as $\delta_{\rm PMNS}\approx-\frac{\pi}{2}$. The PMNS lepton mixing angles in the SM is parametrized by

$$\begin{pmatrix} C_1 & S_1C_3 & S_1S_3 \\ -C_2S_1 & -e^{-i\delta}S_2S_3+C_1C_2C_3 & e^{-i\delta}S_2C_3+C_1C_2S_3 \\ e^{i\delta}S_1S_2 & -C_2S_3-C_1S_2C_3e^{i\delta} & C_2C_3-C_1S_2S_3e^{i\delta} \end{pmatrix} \tag{2.1}$$

where $\delta=\delta_{\rm PMNS}$, and $C_i=\cos\Theta_i$ and $S_i=\sin\Theta_i$. Because $\delta_{\rm PMNS}$ is non-zero, let us look for

[1] To prove the maximality with the observed real angles in the CKM parametrization [8], one must slightly vary the real angles also since γ is not close to $\frac{\pi}{2}$.

leptogenesis mechanism which includes $\delta_{\rm PMNS}$ explicitly.

3. Type-II leptogenesis

It is known that the sphaleron processes at the electroweak scale changes B and L numbers but conserves $B-L$. At the electroweak scale, the sphaleron conversion of L to B or vice versa gives the final B and L proportional to the initial $B-L$. Since the SU(5) GUT conserves $B-L$, thus the early GUT idea [11] on baryogenesis seems not working.

For non-zero final baryon number, generation of B and L at high temperature must occur through processes which generate nonzero $B-L$. In GUTs, therefore, we use the $B-L$ breaking interaction in SO(10), for example. In the beyond SM (BSM) with singlets, we can use a singlet N, called "heavy neutrino" at high energy scale, to generate just L. The early idea was to define a right(left)-handed N with lepton number $L=+1(-1)$ [2]. In fact, the definition of lepton number, related to neutrino masses, is a combination of defining the lepton number of the up-type Higgs doublets together with that of N. The leptogenesis with the definition of $L=+1$ for N_R is called here 'Type-I leptogenesis' [2].

'Type-II leptogenesis' is proposed [1] under a different definition on L from that of Type-I and the electroweak symmetry breaking at high temperature. There exists a finite region of parameter space in the multi-Higgs model that the electroweak symmetry is broken at high temperature [12]. In SUSY, the electroweak symmetry breaking at high temperature is more probable since the temperature dependent terms in V are SUSY breaking terms.

The lepton number is defined with the left-handed SM doublets $\ell_i(\ni \nu_{e,\mu,\tau})$ carrying $L=+1$. Weinberg's effective operator for neutrino masses is [13]

$$\mathscr{L}_Y \propto \frac{f_{ij}}{M}\ell_i\ell_j h_u h_u \tag{3.1}$$

where h_u is the up-type Higgs doublet. Non-zero neutrino masses break L. So, as far as $\langle h_u\rangle = 0$, neutrinos do not obtain mass by the above operator. Therefore, L can be properly defined below the scale of $\langle h_u\rangle \neq 0$. One may argue that there is also h_d, which is exactly the reason that h_u can carry a global quantum number, because both h_u and h_d can together define a gauge charge Y and a global charge L. To do so, in fact we need 'inert' SU(2) doublets $H_{u,d}$.

The effective interaction (3.1) is realized in terms of two renormalizable operators

$$M_0 NN,\ \ell N h_u \tag{3.2}$$

where M_0 in our jargon is the 'messenger' mass, connecting N and ν, which is the so-called "see-saw" mechanism, first suggested with a humdrum title in [14]. But, for neutrino masses at low energy, "who cares about renormalizable interactions ?", as noticed in many mechanisms for neutrino masses under the name of Type$_I$, Type$_{II}$, and Type$_{III}$.

However, in cosmology it matters because in the cosmic history the cosmic temperature T has swept all possible energy scales of particle physics. One can define the *lepton number L* such that (3.1) gives the neutrino masses.

In Type-I leptogenesis, Figs. 3 (a), (c), and (d) are considered where both the L violation and CP violation appear in blue bullets. We need at least two N's for the interference of Figs. 3 (a), (c),

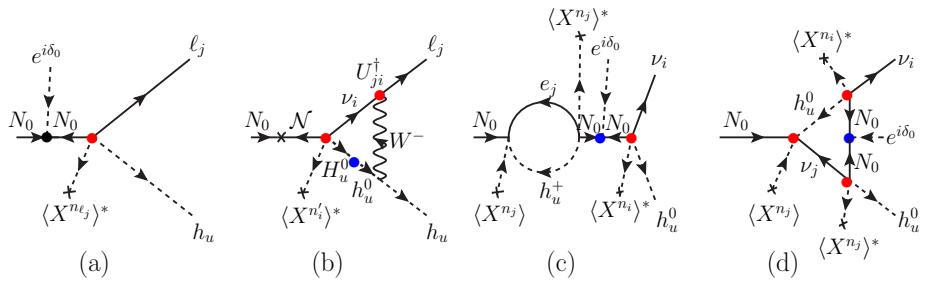

Figure 3: The Feynman diagrams interfering in the N decay: (a) the lowest order diagram, (b) the W exchange diagram, (c) the wave function renormalization diagram, and (d) the heavy neutral lepton exchange diagram. There exist similar $\mathcal{N}$-decay diagrams. In all figures, the final leptons can be both charged leptons and neutrinos. The lepton number violations are inserted with blue bullets and phases are inserted at red bullets. (a) and (b) interfere. (c) and (d) give a vanishing contribution in N_0 domination with one complex VEV.

	ℓ_L	H_u	H_d	$h_{u,d}$	N	$\mathcal{N}$
Type-II leptogen.	$+1$	-2	$+2$	0	-1	$+1$
VEV	$\times$	inert	inert	$v_{\rm ew}\{s_\beta, c_\beta\}$	$\times$	$\times$

Table 1: Definition of lepton numbers in Type-II leptogeneses. We introduced an inert Higgs H_u carrying $L=-2$ with zero VEV and singlet leptons $\mathcal{N}$ carrying $L=+1$.

and (d). So, if there is a hierarchy of masses such as $m_{N_0}/m_{N_1} \ll 1$, then the lepton asymmetry is suppressed by that factor.

In Type-II leptogenesis, the lepton number is defined differently as shown in Table 1. We need an inert Higgs doublet H_u carrying $L=-2$ and singlet leptons $\mathcal{N}$ carrying $L=+1$. The relevant leptogenesis diagrams are those given in Figs. 3 (a) and (b). Here, the lepton number violation appears in blue bullets and the CP violation appears in red bullets. Anyway, the fields $H_{u,d}$ and $\mathcal{N}$ introduced at high energy scale are not visible at low energy scale. We introduce interactions $N_0\ell_L h_u$, $\mathcal{N}_0\ell_L H_u$, $N_0\mathcal{N}_0$, $H_u H_d, \cdots$, conserving L, and $h_u^* H_u$, $N_0 N_0$, $\mathcal{N}_0\mathcal{N}_0, \cdots$, violating L.

For Fig. 3 (b) to be useful for leptogenesis at a high temperature, we must have W boson is not massless, *i.e.* SU(2)×U(1) symmetry is broken at the high temperature. Indeed, such possibility has been suggested long time ago [12]. Furthermore, in models with only one CP phase in an ultraviolet completed theory, leptogenesis phase can be related to the PMNS phase. Even, phases of heavy neutrinos, $N_0, \cdots$, are expressible in terms of this fundamental phase [9].

Within this framework, we calculated the lepton asymmetry which turned out to be consistent with the fact that in these diagrams the lepton violation is on the left side of the cut diagram [1], and a more complete calculation will be presented [15].

4. Conclusion

Here, a brief discussion on Type-II leptogenesis is centered on: (1) A review on weak CP, (2) Introduction of a new leptogenesis mechanism in theories with SU(2)×U(1) breaking at high

temperature, (3) Relation of $\delta_{\rm PMNS}$ to the leptogenesis phase in certain CP violation models, (4) Need of one light intermediate scale Majorana neutrino N_0 and another neutrino $\mathcal{N}$ toward the desired lepton number asymmetry ε_L, and (5) Inert Higgs and the SM Higgs mix to provide $\Delta L \neq 0$ vertex in the loop diagram.

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