Physics Letters B 785 (2018) 184–190

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Pendulum Leptogenesis

Kazuharu Bamba [a], Neil D. Barrie [b], Akio Sugamoto [c,d], Tatsu Takeuchi [e], Kimiko Yamashita [c,f,g,h]

[a] Division of Human Support System, Faculty of Symbiotic Systems Science, Fukushima University, Fukushima 960-1296, Japan
[b] Kavli IPMU (WPI), UTIAS, University of Tokyo, Kashiwa, Chiba 277-8583, Japan
[c] Department of Physics, Graduate School of Humanities and Sciences, Ochanomizu University, 2-1-1 Ohtsuka, Bunkyo-ku, Tokyo 112-8610, Japan
[d] Tokyo Bunkyo SC, The Open University of Japan, Tokyo 112-0012, Japan
[e] Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA
[f] Program for Leading Graduate Schools, Ochanomizu University, 2-1-1 Ohtsuka, Bunkyo-ku, Tokyo 112-8610, Japan
[g] Department of Physics, National Tsing Hua University, Hsinchu, 300 Taiwan
[h] Physics Division, National Center for Theoretical Sciences, Hsinchu, 300 Taiwan

ARTICLE INFO

Article history:
Received 13 May 2018
Received in revised form 2 August 2018
Accepted 27 August 2018
Available online 28 August 2018
Editor: J. Hisano

ABSTRACT

We propose a new non-thermal Leptogenesis mechanism that takes place during the reheating epoch, and utilizes the Ratchet mechanism. The interplay between the oscillation of the inflaton during reheating and a scalar lepton leads to a dynamical system that emulates the well-known forced pendulum. This is found to produce driven motion in the phase of the scalar lepton which leads to the generation of a non-zero lepton number density that is later redistributed to baryon number via sphaleron processes. This model successfully reproduces the observed baryon asymmetry, while simultaneously providing an origin for neutrino masses via the seesaw mechanism.

1. Introduction

One of the major unsolved problems in modern physics is the origin of the observed baryon asymmetry of the universe. The size of the baryon asymmetry is parametrized by the asymmetry parameter η_B [1],

$$\eta_B = \frac{n_B}{s} \simeq 8.5 \times 10^{-11} \,, \tag{1}$$

where n_B and s are respectively the baryon number and entropy densities of the universe.

Any $\mathcal{CPT}$ conserving model that wishes to generate this asymmetry must satisfy the so called Sakharov conditions [2]. Although the Standard Model of particle physics does so, it is unable to reproduce a large enough asymmetry, and hence new physics is required. It is usually assumed that the baryon asymmetry at the end of the inflationary epoch was negligibly small or zero, due to the rapid dilution of any initial baryon number density that may have existed. Due to this, most mechanisms of Baryogenesis are assumed to occur after inflation; during the reheating or subsequent epochs prior to Big Bang Nucleosynthesis.

In what follows we shall outline a new mechanism for Leptogenesis in which lepton number generation is driven by the oscillations of the inflaton field. Leptogenesis is a widely studied paradigm that was first suggested in Ref. [3,4], in which the baryon asymmetry is proposed to have originated in the leptonic sector. Once the lepton asymmetry is generated it is converted to baryon number via $B+L$ violating sphaleron transitions which are in thermal equilibrium prior to the electroweak phase transition [5–7]. See also Ref. [8].

The new Leptogenesis mechanism we propose here acts during the reheating epoch, and is inspired by the ratchet models that describe molecular motors in biological systems [9] and the potential application of it to Baryogenesis [10]. In a previous work [11] we considered a toy model consisting of a scalar baryon and inflaton, embedded in the ratchet framework, which aimed to successfully generate the observed baryon asymmetry. Here, we explore more deeply this mechanism from the perspective of Leptogenesis, providing a source for Baryogenesis and simultaneously providing an origin for the neutrino masses.

E-mail addresses: bamba@sss.fukushima-u.ac.jp (K. Bamba), neil.barrie@ipmu.jp (N.D. Barrie), sugamoto.akio@ocha.ac.jp (A. Sugamoto), takeuchi@vt.edu (T. Takeuchi), kimikoy@phys.nthu.edu.tw (K. Yamashita).

https://doi.org/10.1016/j.physletb.2018.08.044

2. Description of the model

We construct a model consisting of two scalar fields – a real scalar field Φ that we identify as the inflaton, and a complex scalar lepton ϕ. Complex scalars were first utilised for the purposes of Baryogenesis in the Affleck–Dine mechanism [15]. In the ensuing analysis we assume that the dynamics during reheating are dictated by these two scalars and only consider interactions of the inflaton with Standard Model fields via an effective friction term Γ that fixes the reheating temperature. The scalar lepton ϕ also has a friction term associated with its decay to right handed neutrinos. The model is described by the following action:

$$S = \int d^4x \sqrt{-g}\Big[g_{\mu\nu}\,\partial^\mu\phi^*\partial^\nu\phi - V(\phi,\phi^*) + \frac{1}{2}\,g_{\mu\nu}\,\partial^\mu\Phi\,\partial^\nu\Phi - U(\Phi) + \frac{i}{\Lambda}g_{\mu\nu}\big(\phi^*\overleftrightarrow{\partial^\mu}\phi\big)\partial^\nu\Phi\Big], \quad (2)$$

where $U(\Phi)$ is the inflationary potential, and $V(\phi,\phi^*)$ is the scalar lepton potential. The form of the interaction between ϕ and Φ is analogous to that used as in the Baryogenesis mechanism considered in Ref. [12–14]. This interaction term is suppressed by the cutoff scale Λ. In the absence of the $V(\phi,\phi^*)$ term, this action is invariant under a $U(1)$ symmetry which we identify with lepton number, under which ϕ has charge 2. The potential $V(\phi,\phi^*)$ is assumed to include a term which breaks this symmetry explicitly.

A key ingredient of our mechanism is the dynamics of the inflaton during reheating. To set up pendulum like dynamics we require that the inflationary potential approaches an $m^2\Phi^2$ like potential during reheating. There are various inflationary models that exhibit this behaviour, including the well-known Starobinsky inflationary scenario which is in good agreement with current observational constraints [1,16]. For illustration purposes, we will discuss our mechanism within the context of the Starobinsky inflationary scenario.[1] In this case, we have the following inflationary potential,

$$U(\Phi) = \frac{3\mu^2M_p^2}{4}\Big(1-e^{-\sqrt{2/3}\Phi/M_p}\Big)^2 = \frac{1}{2}\mu^2\Phi^2 + \cdots \quad (3)$$

where $\mu = (1.3\times10^{-5})M_p$ is the inflaton mass, and $M_p = 2.4\times10^{18}$ GeV is the reduced Planck mass. The reheating period in the Starobinsky model is defined by an $\frac{1}{2}\mu^2\Phi^2$ potential, leading to the epoch being characterised by a time averaged Hubble rate that is analogous to the Hubble rate of a matter dominated epoch [20]. The reheating epoch in this scenario is characterised by the following initial parameters, from numerical calculations: $\Phi_i = \Phi(t_i) = 0.62\,M_p$, with a corresponding Hubble parameter of $H_i = H(t_i) = 6.2\times10^{12}$ GeV [21].

We consider the potential associated with the scalar lepton to include an explicit lepton breaking term of the following form[2]:

$$V(\phi,\phi^*) = V_0\left(|\phi|^2\right) - \lambda\,\phi\phi^*(\phi-\phi^*)^2\,. \quad (4)$$

Hence, the action during reheating is,

$$S = \int d^4x\sqrt{-g}\Big[g_{\mu\nu}\,\partial^\mu\phi^*\partial^\nu\phi + \lambda\phi\phi^*(\phi-\phi^*)^2 + \frac{1}{2}\,g_{\mu\nu}\,\partial^\mu\Phi\,\partial^\nu\Phi - \frac{1}{2}\mu^2\Phi^2 + \frac{i}{\Lambda}g_{\mu\nu}\big(\phi^*\overleftrightarrow{\partial^\mu}\phi\big)\partial^\nu\Phi\Big], \quad (5)$$

where we have neglected terms associated with $V(|\phi|^2)$ which will not be important for our analysis. It is clear that if $\lambda = 0$, the action will be invariant under the global $U(1)_L$ symmetry defined by the transformation $(\phi,\phi^*)\to(e^{-2i\alpha}\phi, e^{2i\alpha}\phi^*)$, where α is a constant. This transformation has the corresponding lepton number current,

$$j_L^\mu = -2i\left(\phi\,\partial^\mu\phi^* - \phi^*\partial^\mu\phi\right) + \frac{4|\phi|^2}{\Lambda}\,\partial^\mu\Phi\,. \quad (6)$$

We now wish to consider the following polar coordinate parametrization of the ϕ field, $\phi = \frac{1}{\sqrt{2}}\phi_r e^{i\theta}$. Under the global lepton number transformation, the phase θ transforms as $\theta\to\theta-2\alpha$, while ϕ_r is invariant. In this parametrization the conserved lepton number density, which corresponds to the time component of Eq. (6), is given by,

$$n'_L = j^0 = -2\phi_r^2\left(\dot\theta - \frac{\dot\Phi}{\Lambda}\right). \quad (7)$$

The non-conserved physical net lepton number density is that from the free-field Lagrangian,

$$n_L = -2\phi_r^2\dot\theta\,. \quad (8)$$

This implies that within the framework of our mechanism we must produce a non-zero $\dot\theta$, a period of driven motion, to have a net lepton asymmetry generated. In the rest of our analysis, we assume that the terms that only depend on ϕ_r in V are such that they keep ϕ_r approximately fixed to a constant non-zero value, and that only the dynamics of the phase θ need be considered.

Seeing as we wish to consider the cosmological setting of reheating, we take the flat FRW metric with scale factor $a(t)$. Given this isotropic and homogeneous background, we extend this assumption to the properties of the scalar lepton and inflaton, for which spatial variation will be ignored in our analysis. Therefore, in the new parametrization of the scalar lepton and in a flat FRW background, the action takes the form,

$$S = \int dt\, a(t)^3\left[\frac{\phi_r^2}{2}\,\dot\theta^2 - \lambda\,\phi_r^4\sin^2\theta + \frac{1}{2}\,\dot\Phi^2 - \frac{1}{2}\,\mu^2\Phi^2 - \frac{\phi_r^2}{\Lambda}\,\dot\theta\,\dot\Phi\right]. \quad (9)$$

This action illustrates how the Sakharov conditions are satisfied in our model. Firstly, L violation is achieved by the potential $V_{\rm int} = \lambda\phi_r^4\sin^2\theta$, which breaks the translational invariance in θ. Secondly, the derivative coupling between θ and Φ provides $\mathcal{C}$ and $\mathcal{CP}$ violation. Lastly, the required push out-of-equilibrium will be provided by the reheating epoch, induced by the coherent oscillation of the inflaton field. The lepton number asymmetry generated during reheating shall then be redistributed into a net baryon number by the action of $B-L$ conserving sphaleron processes [5,7,8].

The generated lepton asymmetry will be produced in the form of right handed neutrinos, via the preferential decay of ϕ during the period of driven motion. To achieve this, we introduce the lepton-number preserving dimension four interactions,

$$\Delta\mathcal{L}_{\rm int} = \left(g_L\phi^*\overline{\nu_R^c}\nu_R + y_H H\bar{L}\nu_R\right) + {\rm h.c.} \quad (10)$$

[1] In the Starobinsky context, the introduced derivative coupling term is analogous to that considered in [17]. It has recently been shown that such a coupling may be incompatible with cosmological observations [18,19].

[2] Through introducing an additional scalar lepton φ, we may naturally realize a potential of this form via spontaneous symmetry breaking $\langle\varphi\rangle \neq 0$. In order for this mechanism to work, however, the Nambu–Goldstone boson associated with this spontaneous breaking must be eliminated.