Baryogenesis in cosmological model with superstring-inspired E_6 unification

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A R T I C L E   I N F O

A B S T R A C T

We have developed a concept of parallel existence of the ordinary (O) and hidden (H) worlds with a superstring-inspired E_6 unification, broken at the early stage of the Universe into $SO(10) \times U(1)$ – in the O-world, and $SU(6)' \times SU(2)'$ – in the H-world. As a result, we have obtained in the hidden world the low energy symmetry group $G'_{SM} \times SU(2)'_\theta$, instead of the Standard Model group G_{SM}. The additional non-Abelian $SU(2)'_\theta$ group with massless gauge fields, "thetons", is responsible for the dark energy. We present a baryogenesis mechanism with the $B - L$ asymmetry produced by the conversion of ordinary leptons into particles of the hidden sector.

1. Introduction

A cosmological model has been proposed in Ref. [1] with the superstring-inspired E_6 unification arising at the early stage of the Universe. Considering a parallel existence of the ordinary (O) and hidden (H) worlds, it was assumed that the E_6 group was broken differently in the O- and H-sectors with the following breakings:

$$E_6 \rightarrow SO(10) \times U(1) \tag{1}$$

– in the O-world, and

$$E_6' \rightarrow SU(6)' \times SU(2)' \tag{2}$$

– in the H-world.[1]

Using the model [1], we have tried to explain the origin of the Dark Energy (DE), Dark Matter (DM) and visible matter with energy densities given by recent cosmological observations, confirming the ΛCDM cosmological model with a tiny value of the cosmological constant. The study [1] is a development of the ideas considered previously in Refs. [2]. In the present investigation we

describe the inflation epoch of our Universe and baryogenesis scenario.

For the present epoch, the Hubble parameter $H = H_0$ is given by the following value [3,4]:

$$H_0 = 1.5 \times 10^{-42} \text{ GeV} \tag{3}$$

and the critical density of the Universe is

$$\rho_c = 3H^2/8\pi G = \left(2.5 \times 10^{-12} \text{ GeV}\right)^4. \tag{4}$$

Cosmological measurements give the following density ratios of the total Universe [3,4]:

$$\Omega = \Omega_r + \Omega_m + \Omega_\Lambda = 1, \tag{5}$$

where $\Omega_r \ll 1$ is a relativistic (radiation) density ratio and

$$\Omega_\Lambda = \Omega_{DE} \sim 75\% \tag{6}$$

for the mysterious Dark Energy (DE), which is responsible for the accelerated expansion of the Universe. The matter density ratio is:

$$\Omega_m \approx \Omega_M + \Omega_{DM} \sim 25\%, \tag{7}$$

with $\Omega_M \approx \Omega_B \approx 4\%$ – for (visible) baryons, and $\Omega_{DM} \approx 21\%$ – for the Dark Matter (DM). We can calculate the dark energy density using (4) and (6):

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[1] The superscript 'prime' denotes the H-world.

$$\rho_{DE} = \rho_{vac} \approx 0.75\rho_c \approx \left(2.3 \times 10^{-3} \text{ eV}\right)^4. \tag{8}$$

The result (8) is consistent with the present model of accelerating Universe dominated by a tiny cosmological constant and Cold Dark Matter (CDM).

2. Superstring theory and E_6 unification

Superstring theory [5–7] is a paramount candidate for the unification of all fundamental gauge interactions with gravity. The 'heterotic' superstring theory $E_8 \times E_8'$ reasonably was suggested as a realistic model for unification of all fundamental gauge interactions with gravity [6]. This ten-dimensional theory can undergo spontaneous compactification. The integration over six compactified dimensions of the E_8 superstring theory leads to the effective theory with the E_6 unification in the four-dimensional space [7].

Superstring theory has led to the speculation that there may exist another form of matter – hidden "shadow matter" – in the Universe, which only interacts with ordinary matter via gravity or gravitational-strength interactions [8] (see also the reviews [9]). The shadow world, in contrast to the mirror world [10], can be described by another group of symmetry (or by a chain of groups of symmetry), which is different from the ordinary world symmetry group.

Three 27-plets of E_6 contain three families of quarks and leptons, including right-handed neutrinos N_i^c (where $i = 1, 2, 3$ is the index of generations). We omit generation subscripts, for simplification.

Matter fields (quarks, leptons and scalar fields) of the fundamental 27-representation of the E_6 group decompose under $SU(5) \times U(1)_X$ subgroup as follows (see Ref. [11]):

$$27 \to (10, 1) + (\bar{5}, 2) + (5, -2) + (\bar{5}, -3) + (1, 5) + (1, 0). \tag{9}$$

The first and second numbers in the brackets in Eq. (9) correspond to the dimensions of the $SU(5)$ representations and to the $U(1)_X$ charges, respectively. These representations decompose under the groups with the breaking

$$SU(5) \times U(1)_X \to SU(3)_C \times SU(2)_L \times U(1)_Z \times U(1)_X. \tag{10}$$

We consider the following $U(1)_Z \times U(1)_X$ charges of matter fields: $Z = \sqrt{\frac{5}{3}} Q^Z, \ X = \sqrt{40} Q^X$.

The Standard Model (SM) family which contains the doublets of left-handed quarks Q and leptons L, right-handed up and down quarks u^c, d^c, and also right-handed charged lepton e^c, belongs to the $(10, 1) + (\bar{5}, 2)$ representations of $SU(5) \times U(1)_X$. Then, for the decomposition (10), we have the following assignments of particles:

$$(10, 1) \to Q = \begin{pmatrix} u \\ d \end{pmatrix} \sim \left(3, 2, \frac{1}{6}, 1\right),$$

$$u^{\mathbf{c}} \sim \left(\bar{3}, 1, -\frac{2}{3}, 1\right),$$

$$e^{\mathbf{c}} \sim (1, 1, 1, 1), \tag{11}$$

$$(\bar{5}, 2) \to d^{\mathbf{c}} \sim \left(\bar{3}, 1, \frac{1}{3}, 2\right),$$

$$L = \begin{pmatrix} e \\ \nu \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}, 2\right), \tag{12}$$

$$(1, 5) \to S \sim (1, 1, 0, 5). \tag{13}$$

The remaining representations in (10) decompose as follows:

$$(5, -2) \to D \sim \left(3, 1, -\frac{1}{3}, -2\right),$$

$$h = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix} \sim \left(1, 2, \frac{1}{2}, -2\right). \tag{14}$$

$$(\bar{5}, -3) \to D^{\mathbf{c}} \sim \left(\bar{3}, 1, \frac{1}{3}, -3\right),$$

$$h^{\mathbf{c}} = \begin{pmatrix} h^0 \\ h^- \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}, -3\right). \tag{15}$$

To the representation $(1, 5)$ is assigned the SM-singlet field S, which carries non-zero $U(1)_X$ charge. The light Higgs doublets are accompanied by the heavy colour triplets of exotic quarks ('diquarks') $D, D^{\mathbf{c}}$ which are absent in the SM (see Ref. [11]).

The right-handed heavy neutrino is a singlet field N^c represented by $(1, 0)$:

$$(1, 0) \to N^{\mathbf{c}} \sim (1, 1, 0, 0). \tag{16}$$

3. Breaking of the E_6 unification in cosmology

The results of Refs. [12] are based on the hypothesis of the existence in Nature a mirror (M) world parallel to the visible ordinary (O) world. The authors have described the O- and M-worlds at low energies by a minimal symmetry $G_{SM} \times G'_{SM}$ where

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

stands for the observable Standard Model (SM) while

$$G'_{SM} = SU(3)'_C \times SU(2)'_L \times U(1)'_Y$$

is its mirror gauge counterpart. The M-particles are singlets of G_{SM} and the O-particles are singlets of G'_{SM}. These different O- and M-worlds are coupled only by gravity, or possibly by another very weak interaction.

If the ordinary and mirror worlds are identical, then O- and M-particles should have the same cosmological densities. But this is immediately in conflict with recent astrophysical measurements. Mirror parity (MP) is not conserved, and the ordinary and mirror worlds are not identical. Then the VEVs of the Higgs doublets ϕ and ϕ' are not equal:

$$\langle\phi\rangle = v, \qquad \langle\phi'\rangle = v' \quad \text{and} \quad v \neq v'. \tag{17}$$

Introducing the parameter characterizing the violation of MP:

$$\zeta = \frac{v'}{v} \gg 1, \tag{18}$$

we have the estimate of Refs. [12]: $\zeta \sim 100$. Then the masses of fermions and massive bosons in the mirror world are scaled up by the factor ζ with respect to the masses of their counterparts in the ordinary world:

$$m'_{q',l'} = \zeta m_{q,l}, \qquad M'_{W',Z',\Phi'} = \zeta M_{W,Z,\Phi}, \tag{19}$$

while photons and gluons remain massless in both worlds.

In contrast to Refs. [12], in the present Letter we consider a cosmological model with E_6 unification when at the early stage of the Universe the O- and H (actually M)-worlds have the same GUT-scales and GUT-coupling constants: $M_{E6} = M'_{E6'}$ and $g_{E6} = g'_{E6'}$. Later the E_6 unification undergoes breakings which are different for O- and H-worlds.

It is well known (see [13]) that there exist the following three schemes for breaking of the E_6 group:

i) $\quad E_6 \to SU(3)_1 \times SU(3)_2 \times SU(3)_3,$ $\qquad(20)$

ii) $\quad E_6 \to SO(10) \times U(1),$ $\qquad(21)$

iii) $\quad E_6 \to SU(6) \times SU(2).$ $\qquad(22)$

The first case was considered in Ref. [1], where the possibility of the breaking

$$E_6 \to SU(3)_C \times SU(3)_L \times SU(3)_R \qquad (23)$$

was investigated in the ordinary and mirror worlds, assuming broken mirror parity. The model has the merit of an attractive simplicity. However, in such a model one is unable to explain the tiny value of cosmological constant given by astrophysical measurements, because in the case (23) we have in both worlds the low-energy limit of the Standard Model (SM), which forbids a large confinement radius (i.e. small energy scale) of any interaction.

It is impossible to obtain the same E_6 unification in the O- and M-worlds with the same breakings ii) or iii) if the mirror parity is broken in the Universe. In this case, we are forced to assume different breakings, (1) and (2), of the E_6 unification in the O- and H-worlds. Since astrophysical measurements confirm zero contributions to the dark energy from both SM and SM′ sectors, we explain the small value of the cosmological constant $\Lambda = \rho_{vac} = \rho_{DE}$ by condensation of fields belonging to the additional $SU(2)'$ gauge group which exists only in the H-world and has a large confinement radius.

The breaking mechanism of the E_6 unification is given in Ref. [14]. The vacuum expectation values (VEVs) of the Higgs fields H_{27} and H_{351} belonging to 27- and 351-plets of the E_6 group can appear in the case (1) only with non-zero 27-component:

$$\langle H_{351} \rangle = 0, \qquad v = \langle H_{27} \rangle \neq 0. \qquad (24)$$

In the case (2) we have

$$\langle H_{27} \rangle = 0, \qquad V = \langle H_{351} \rangle \neq 0. \qquad (25)$$

The 27 representation of E_6 is decomposed into $1 + 16 + 10$ under the $SO(10)$ subgroup and the 27 Higgs field H_{27} is expressed in 'vector' notation as

$$H_{27} \equiv \begin{pmatrix} H_0 \\ H_\alpha \\ H_M \end{pmatrix}, \qquad (26)$$

where the subscripts 0, $\alpha = 1, 2, \ldots, 16$ and $M = 1, 2, \ldots, 10$ stand for singlet, the 16- and the 10-representations of $SO(10)$, respectively. Then

$$\langle H_{27} \rangle = \begin{pmatrix} v \\ 0 \\ 0 \end{pmatrix}. \qquad (27)$$

Taking into account that the 351-plet of E_6 is constructed from 27×27 symmetrically, we see that the trace part of H_{351} is a singlet under the maximal little groups. Therefore, in a suitable basis, we can construct the VEV $\langle H_{351} \rangle$ for the case of the maximal little group $SU(2) \times SU(6)$. A singlet under this group which we get from a symmetric product of 27×27 comes from the component $(1, 15) \times (1, 15)$ and hence

$$\langle H_{351} \rangle = \begin{pmatrix} V \otimes 1_{15} & \\ & 0 \otimes 1_{15} \end{pmatrix}. \qquad (28)$$

According to the assumptions of Ref. [1], in the ordinary world, from the Standard Model (SM) scale up to the E_6 unification, there exists the following chain of symmetry groups:

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$
$$\to \left[SU(3)_C \times SU(2)_L \times U(1)_Y \right]_{SUSY}$$
$$\to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z$$
$$\to SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_Z$$
$$\to SO(10) \times U(1)_Z \to E_6. \qquad (29)$$

In the shadow H-world, we have the following chain of symmetry groups:

$$SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y$$
$$\to \left[SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y \right]_{SUSY}$$
$$\to SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_X \times U(1)'_Z$$
$$\to SU(4)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Z$$
$$\to SU(6)' \times SU(2)'_\theta \to E'_6. \qquad (30)$$

In general, this is not an unambiguous choice of the $E_6(E'_6)$ breaking chains.

4. Shadow theta particles

In the present Letter we assume the existence of the shadow low-energy symmetry group:

$$G' = SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y, \qquad (31)$$

with an additional non-Abelian $SU(2)'_\theta$ group whose gauge fields are neutral, massless vector particles – thetons (see Ref. [15]). This is a natural consequence of different schemes of the E_6-breaking in the O- and H-worlds. By analogy with the theory developed in [15], we consider shadow thetons $\Theta'^i_{\mu\nu}$, $i = 1, 2, 3$, which belong to the adjoint representation of $SU(2)'_\theta$, three generations of shadow theta-quarks q'_θ and shadow leptons l'_θ, and the necessary theta-scalars ϕ'_θ for the corresponding breakings. The theta-particles are absent in the ordinary world (they are not confirmed by experiment), however, they can exist in the hidden world. We assume that shadow thetons have the macroscopic confinement radius $1/\Lambda'_\theta$, where $\Lambda'_\theta \sim 10^{-3}$ eV.

5. Inflation, E_6 unification and the problem of walls in the Universe

The simplest model of inflation is based on the superpotential

$$W = \lambda \varphi (\Phi^2 - \mu^2), \qquad (32)$$

containing the inflaton field given by φ and the Higgs field Φ, where λ is a coupling constant of order 1 and μ is a dimensional parameter of the order of the GUT scale. The supersymmetric vacuum is located at $\varphi = 0$, $\Phi = \mu$, while for the field values $\Phi = 0$, $|\varphi| > \mu$ the tree level potential has a flat valley with the energy density $V = \lambda^2 \mu^4$. When the supersymmetry is broken by the non-vanishing F-term, the flat direction is lifted by radiative corrections and the inflaton potential acquires a slope appropriate for the slow roll conditions.

This so-called hybrid inflation model leads to the choice of the initial conditions [16]. Namely, at the end of the Planck epoch the singlet scalar field φ should have an initial value $\varphi = f \sim 10^{18}$ GeV (E_6-GUT scale), while the field Φ must be zero with high accuracy over a region much larger than the initial horizon size $\sim M_{Pl}$. In other words, the initial field configuration should be located right on the bottom of the inflaton valley and the energy density starts with $V = \lambda^2 \mu^4 \ll M_{Pl}^4$.

If E_6' is the mirror counterpart of E_6, then we have Z_2 symmetry, i.e. a discrete group connected with the mirror parity. In general, the spontaneous breaking of a discrete group leads to phenomenologically unacceptable walls of huge energy per area. Then we have the following properties for the energy densities of radiation, DM, M and wall:

$$\rho_r \propto \frac{1}{a(t)^4}, \qquad \rho_{M,DM} \propto \frac{1}{a(t)^3}, \qquad \rho_{wall} \propto \frac{1}{a(t)},$$

where $a(t)$ is a scale factor with cosmic time t in the Friedmann–Lemaitre–Robertson–Walker (FLRW) metric describing our Universe. For large Universe we have $\rho_{wall} \gg \rho_{M,DM}, \rho_r$. In our case of the hidden world, the shadow superpotential is:

$$W' = \lambda' \varphi' (\Phi'^2 - \mu'^2), \tag{33}$$

where $\Phi' = H_{351}$ and $\langle H_{351} \rangle = \mu'$. Then the initial energy density in the H-world is $V' = \lambda'^2 \mu'^4 \ll M_{Pl}^4$. To avoid this phenomenologically unacceptable wall dominance we cannot assume symmetry under Z_2 and thus $V = V'$ is not automatic. Instead, it is necessary to assume the following fine-tuning:

$$V = V': \quad \lambda^2 \mu^4 = \lambda'^2 \mu'^4, \tag{34}$$

which helps to obtain the initial conditions for the GUT-scales and GUT-coupling constants: $M_{E6} = M'_{E6'}$ and $g_{E6} = g'_{E6'}$.

6. Quintessence model of cosmology. Inflaton and axion

Quintessence is described by a complex scalar field φ minimally coupled to gravity.

We assume that there exists an axial $U(1)_A$ global symmetry in our theory, which is spontaneously broken at the scale f by a singlet complex scalar field φ:

$$\varphi = (f + \sigma) \exp(i a_{ax}/f). \tag{35}$$

We assume that a VEV $\langle \varphi \rangle = f$ is of the order of the E_6 unification scale: $f \sim 10^{18}$ GeV. The real part σ of the field φ is the inflaton, while the boson a_{ax} (imaginary part of the singlet scalar fields φ) is an axion and could be identified with the massless Nambu–Goldstone (NG) boson if the corresponding $U(1)_A$ symmetry is not explicitly broken by the gauge anomaly. However, in the hidden world the explicit breaking of the global $U(1)_A$ by $SU(2)_\theta'$ instantons inverts a_{ax} into a pseudo-Nambu–Goldstone (PNG) boson a_θ. Therefore, in the H-world we have:

$$\varphi' = (f + \sigma') \exp(i a_\theta/f). \tag{36}$$

In Ref. [1] we have constructed a quintessence model of cosmology with the axion a_θ, having the mass $m \sim \Lambda_\theta'^2/f \sim 10^{-42}$ GeV. Also we have calculated the dark energy density due to the condensation of the theta-fields:

$$\rho_{DE} = \rho_{vac} = (\Lambda_\theta')^4 \approx (2.3 \times 10^{-3} \text{ eV})^4. \tag{37}$$

That is to say that *provided there were no other contributions*, (37) would be our prediction for the cosmological constant. It is interesting that this value agrees very well with the phenomenological value (8).

The inflaton field provided the mechanism of rapid expansion after the initial expansion that formed the Universe. Any inflationary model has to describe how the SM-particles were generated at the end of inflation. The inflaton, which is a singlet of E_6, can decay, and the subsequent thermalization of the decay products can generate the SM-particles. The inflaton σ produces gauge bosons: photons, gluons, $W^\pm$, Z, and matter fields: quarks, leptons and the

Higgs bosons, while the inflaton field σ' produces H-world particles: shadow photons and gluons, thetons, W', Z', theta-quarks q_θ, theta-leptons l_θ, shadow quarks q' and leptons l', scalar bosons ϕ_θ and shadow Higgs fields ϕ'.

In the shadow world we end up with a thermal bath of SM' and θ particles. However, as it was mentioned above, we assume that the density of θ particles is not too essential in cosmological evolution due to small θ coupling constants.

In the present model and in Refs. [17,18], at the end of inflation the O- and H-sectors are reheated in a non-symmetric way $(T_R > T_R')$. The reheating temperature T_R, at which the inflaton decay and entropy production of the Universe are over, plays a crucial role in cosmological evolution. In our model, after the postinflationary reheating, the shadow sector is cooler than the ordinary one and almost "empty". Therefore, the cosmology of the early H-world is very different from the ordinary one when we consider such crucial epochs as baryogenesis and nucleosynthesis. Any of these epochs is related to an instant when the rate of the relevant particle process, $\Gamma(T)$, becomes equal to the Hubble expansion rate $H(T)$. In the H-world these events take place earlier and the processes freeze out at larger T than in the ordinary world.

7. Baryogenesis

There is currently insufficient evidence to explain why the Universe contains far more baryons than anti-baryons. The first explanation for this phenomenon was given by A.D. Sakharov [19]. The standard mechanism of baryogenesis is based on the following three Sakharov conditions: 1. *B-violation*, which was confirmed by cosmological inflation [20]; 2. Breaking of symmetry between particles and anti-particles, i.e. *C and CP-violation*; 3. *Deviation from thermal equilibrium*.

Neither of these three conditions is obligatory. A lot of models can explain the single observed number:

$$\beta_{observed} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \cdot 10^{-10}, \tag{38}$$

where n_B, $n_{\bar{B}}$, n_γ are baryon, anti-baryon and γ densities, respectively.

In our model, after the non-symmetric reheating with $T_R > T_R'$, the exchange processes between O- and H-worlds are too slow, by reason of the very weak interaction between the two sectors. As a result, it is impossible to establish equilibrium between them, so that both worlds evolve adiabatically and the temperature asymmetry $(T'/T < 1)$ is approximately constant in all epochs from the end of the inflation until the present epoch.

The equilibrium between two sectors of massless particles with the same temperature is not broken by the cosmological expansion, and the baryon asymmetry (and any charge asymmetry) cannot be generated in the Universe. However, if there are two components in the plasma with different temperatures, then the equilibrium is explicitly broken as long as the temperatures are not equal. In our case of observed and hidden sectors, the equilibrium never happens by reason of their essentially different temperatures. In this case, baryon asymmetry may be generated even by scattering of massless particles.

Indeed, due to CP violation, the following cross-sections (with ordinary quarks q and hidden quarks q'):

$$\sigma(q + q \to q' + q') \neq \sigma(\bar{q} + \bar{q} \to \bar{q}' + \bar{q}') \tag{39}$$

are different from each other. If we neglect the inverse process, an asymmetry would be generated. The inverse process can be neglected, being less efficient than the direct one, if the temperature

of the hidden sector is much lower than that of the observed sector. So the baryon asymmetry can be generated even in reactions with massless particles.

In the Bento–Berezhiani model of baryogenesis [17] the heavy Majorana neutrinos play the role of messengers between ordinary and mirror worlds. Their model considers the group of symmetry $G_{SM} \times G_{SM'}$, i.e. the Standard Model and its mirror counterpart. Heavy Majorana neutrinos N are singlets of G_{SM} and $G_{SM'}$ and this is an explanation, why they can be messengers between ordinary and mirror worlds.

In our model with E_6 unification, the N-neutrinos belong to the 27-plet of E_6 and E_6', and they are not singlet particles. But after the breaking

$$E_6 \to SO(10) \times U(1)_Z$$
$$\to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z \quad (40)$$

in the O-world, and

$$E_6' \to \to SU(6)' \times SU(2)_\theta'$$
$$\to SU(3)_C' \times SU(2)_L' \times SU(2)_\theta' \times U(1)_X' \times U(1)_Z' \quad (41)$$

in the H-world, heavy Majorana neutrinos N_a become singlets of the subgroups $SU(3)_C \times SU(2)_L \times U(1)_X \times U(1)_Z$ and $SU(3)_C' \times SU(2)_L' \times U(1)_X' \times U(1)_Z'$, according to Eq. (16). Therefore, in our model [1], after the breaking of $SO(10)$ and $SU(6)'$ and below seesaw scale ($\mu < M_R = M_R' \sim 10^{10-15}$ GeV), when we have the symmetry groups G_{SM} and $G_{SM'} \times SU(2)_\theta'$, the heavy Majorana neutrinos N_a again can play the role of messengers between O- and H-worlds.

Baryon B and lepton L numbers are not perfect quantum numbers. They are directly related to the seesaw mechanism for light neutrino masses. $B - L$ is generated in the decays of heavy Majorana neutrinos, N, into leptons l (or anti-leptons $\bar{l}$) and the Higgs bosons ϕ (which are the standard Higgs doublets):

$$N \to l\phi, \ \bar{l}\bar{\phi}. \quad (42)$$

In this context, the three necessary Sakharov conditions are realized in the following way:

1) $B - L$ and L are violated by the heavy neutrino Majorana masses.
2) The out-of-equilibrium condition is satisfied due to the delayed decay(s) of the Majorana neutrinos, when the decay rate $\Gamma(N)$ is smaller than the Hubble rate H: $\Gamma(N) < H$, i.e. the life-time is larger than the age of the Universe at the time when N_a becomes non-relativistic.
3) CP-violation (C is trivially violated due to the chiral nature of the fermion weak eigenstates) originates as a result of the complex $lN\phi$ Yukawa couplings producing asymmetric decay rates:

$$\Gamma(N \to l\phi) \neq \Gamma(N \to \bar{l}\bar{\phi}), \quad (43)$$

so that leptons and anti-leptons are produced in different amounts and the $B - L$ asymmetry is generated.

In the present model, the quantum numbers B and L are related to the accidental global symmetries existing at the level of renormalizable couplings, which can be explicitly broken by higher order operators with the large mass scale M as a cutoff. In particular, the $D = 5$ operator

$$\mathcal{O}_5 \sim \frac{1}{M}(l\phi)^2 \quad (\Delta L = 2) \quad (44)$$

yields the small Majorana masses for neutrinos according to the seesaw mechanism, $m_\nu \sim v^2/M$, where v is the Higgs VEV given by Eq. (17).

As for the H-sector, the shadow neutrinos get masses via the operator:

$$\mathcal{O}_5' \sim \frac{1}{M}(l'\phi')^2 \quad (\Delta L' = 2), \quad (45)$$

which yields the small Majorana masses for shadow neutrinos: $m_\nu' \sim v'^2/M$, where v' is the shadow Higgs VEV in Eq. (17). However, there can exist also a mixed gauge invariant operator:

$$\mathcal{O}_5^{mix} \sim \frac{1}{M}(l\phi)(l'\phi') \quad (\Delta L = 1, \ \Delta L' = 1), \quad (46)$$

that gives rise to the mixing between the ordinary and shadow neutrinos. All these operators can be induced by the same seesaw mechanism.

Considering n-species (n-generations) of the heavy Majorana neutrinos N_a with the large mass terms $M_N g_{ab} N_a N_b$, we use $M = M_N$ as an overall mass scale. The matrix g_{ab} of dimensionless Yukawa-like constants ($a, b = 1, 2, \ldots, n$) is taken diagonal without lose of generality. Remembering that N_a are gauge singlets, playing the role of messengers between the ordinary and shadow worlds, we assume that they would couple the ordinary leptons $l_i = (\nu, e)_i$ and shadow leptons $l_i' = (\nu', e')_i$ with similar rights:

$$Y_{ia} l_i N_a \phi + Y_{ia}' l_i' N_a \phi'. \quad (47)$$

In the framework of the seesaw mechanism, we obtain the following operators:

$$\mathcal{O}_5 = \frac{A_{ij}}{M}(l_i\phi)(l_j\phi), \qquad \mathcal{O}_5' = \frac{A_{ij}'}{M}(l_i'\phi')(l_j'\phi'),$$
$$\mathcal{O}_5^{mix} = \frac{D_{ij}}{M}(l_i\phi)(l_j'\phi'), \quad (48)$$

with the following coupling constant matrices:

$$A = Y g^{-1} Y^T, \qquad A' = Y' g^{-1} Y'^T, \qquad D = Y g^{-1} Y'^T. \quad (49)$$

The Yukawa constant matrices obey the relation: $Y' = Y^*$, giving $A' = A^*$ and $D = D^+$.
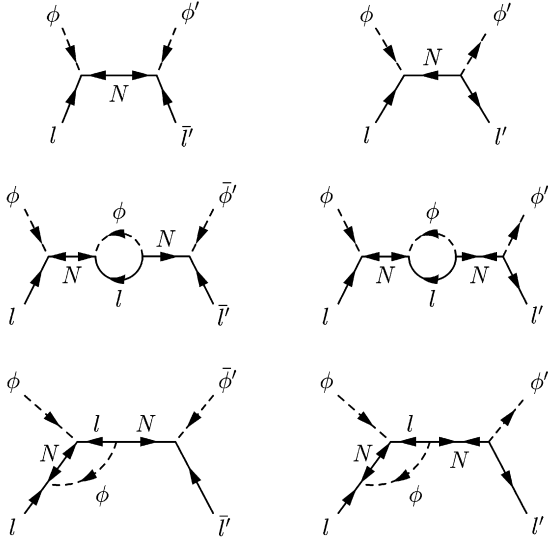
The interactions mediated by heavy neutrinos N_a induce the processes $l\phi \to \bar{l}\bar{\phi}$, etc., in the O-world (with $\Delta L = 2$), $l'\phi' \to \bar{l}'\bar{\phi}'$, etc., in the H-world (with $\Delta L' = 2$), and the processes $l\phi \to \bar{l}'\bar{\phi}'$, etc., with $\Delta L = 1$, $\Delta L' = 1$ that transform O-particles into H-partners.

It is easy to see that all three conditions for baryogenesis [19] are naturally fulfilled:

1) $B - L$ violation is obvious: there are processes which, conserving $B(B')$, violate $L(L')$ and thus both $B - L$ and $B' - L'$.
2) CP violation in these processes is fulfilled due to the complex Yukawa matrices Y and Y'. As a result, the cross-sections with leptons and anti-leptons in the initial state are different from each other. CP-asymmetry emerges in processes with $\Delta L = 1$, as well as with $\Delta L = 2$, due to the interference between the tree-level and one-loop diagrams shown in Refs. [17]. The diagrams relevant for $l\phi \to \bar{l}'\bar{\phi}'$ are shown in Fig. 1. The diagrams responsible for CP-violation in $l\phi \to \bar{l}\bar{\phi}$ and $\bar{l}\bar{\phi} \to l\phi$ are shown in Fig. 2.

The direct calculation gives:

$$\sigma(l\phi \to \bar{l}'\bar{\phi}') - \sigma(\bar{l}\bar{\phi} \to l'\phi') = (-\Delta\sigma - \Delta\sigma')/2,$$
$$\sigma(l\phi \to l'\phi') - \sigma(\bar{l}\bar{\phi} \to \bar{l}'\bar{\phi}') = (-\Delta\sigma + \Delta\sigma')/2,$$
$$\sigma(l\phi \to \bar{l}\bar{\phi}) - \sigma(\bar{l}\bar{\phi} \to l\phi) = \Delta\sigma \quad (50)$$

Fig. 1. Tree-level and one-loop diagrams contributing to the *CP*-asymmetries in the processes $l\phi \to \bar{l}'\bar{\phi}'$ (left column) and $l\phi \to l'\phi'$ (right column). Not all the vertex corrections in the above Feyman diagrams are depicted.
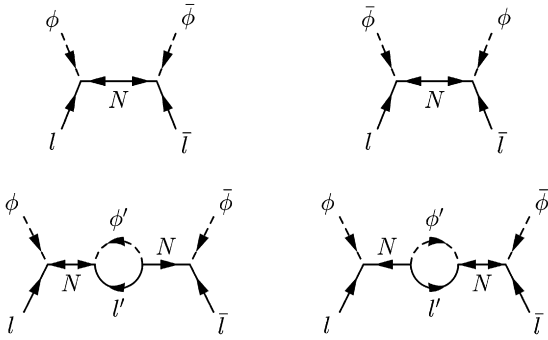
Fig. 2. Tree-level and one-loop diagrams contributing to the CP-asymmetry in the process $l\phi \to \bar{l}\bar{\phi}$. The vertex diagrams corrections are not depicted.

with

$$\Delta\sigma = \frac{3JS}{32\pi^2 M^4}, \qquad \Delta\sigma' = \frac{3J'S}{32\pi^2 M^4}, \tag{51}$$

where S is the c.m. energy square, and J and J' are the CP-violation parameters:

$$J = \mathrm{Im\,Tr}\big[g^{-1}(Y^+Y)^* g^{-1}(Y'^+Y') g^{-2}(Y^+Y)\big],$$
$$J' = \mathrm{Im\,Tr}\big[g^{-1}(Y'^+Y')^* g^{-1}(Y^+Y) g^{-2}(Y'^+Y')\big]. \tag{52}$$

3) All $\Delta L = 1$ processes $l\phi \to l'\phi'$ and $\Delta L = 2$ ones $l\phi \to \bar{l}\bar{\phi}$, $ll \to \phi\phi$ stay out of equilibrium.

Many details of this model can be extracted from Refs. [17].

The reheating temperature T_R, at which the inflaton decay and entropy production of the Universe are over and the relativistic particles are dominated, plays a crucial role in cosmological evolution. In our model and in [17,18] $T' < T$ after the postinflationary reheating, i.e. the shadow sector is cooler than the ordinary one and almost "empty".

The assumption $M_N > T_R$ forbids the thermal production of heavy neutrinos, and the usual leptogenesis mechanism [21] via decays $N \to l\phi$ does not work. However, a net $B - L$ may emerge in the Universe due to the CP-violation in the processes $l\phi \to l'\phi'$.

We see that in our model the baryon asymmetry is generated not only in the O-sector, but also in the H-sector. These two sec-

tors are not identical, but they have similar CP-violating properties due to the complex coupling constants of scattering processes. These processes are most effective at temperatures $T \sim T_R$, although they stay out of equilibrium. Finally, at the relevant epoch, the O-observer detects: (a) the loss of entropy in the O-world due to the leakage of O-particles to the H-world; (b) the leakage of leptons l from O-sector to the H-sector with different rates than anti-leptons $\bar{l}$, and as a result, non-zero $B - L$ in the Universe. In parallel, the H-observer detects: (a′) entropy production in the H-world; (b′) leptons l' and anti-leptons $\bar{l}'$ production with different rates, and non-zero $B' - L'$.

Here it is necessary to comment that the baryon asymmetries in the O- and H-sectors are not equal: by reason that H-world is colder than O-world, the H-baryon asymmetry can be about one order of magnitude bigger than the O-baryon asymmetry. This could explain the difference between the O- and H-worlds.

The present work opens the possibility to specify a grand unification group E_6 from cosmology.

Acknowledgements

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