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Cogenesis in a universe with vanishing $B-L$ within a gauged $U(1)_x$ extension

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ABSTRACT

We consider a gauged $U(1)_x$ extension of the standard model and of the minimal supersymmetric standard model where the dark matter fields are charged under $U(1)_x$ and carry lepton number while the standard model fields and fields of the minimal supersymmetric standard model are neutral under $U(1)_x$. We consider leptogenesis in this class of models with all fundamental interactions having no violation of lepton number, and the total $B-L$ in the universe vanishes. Such leptogenesis leads to equal and opposite lepton numbers in the visible sector and in the dark sector, and thus also produces asymmetric dark matter. Part of the lepton number generated in the leptonic sector subsequently transfer to the baryonic sector via sphaleron interactions. The stability of the dark particles is protected by the $U(1)_x$ gauge symmetry. A kinetic mixing between the $U(1)_x$ and the $U(1)_Y$ gauge bosons allows for dissipation of the symmetric component of dark matter. The case when $U(1)_x$ is $U(1)_{B-L}$ is also discussed for the supersymmetric case. This case is particularly interesting in that we have a gauged $U(1)_{B-L}$ which ensures the conservation of $B-L$ with an initial condition of a vanishing $B-L$ in the universe. Phenomenological implications of the proposed extensions are discussed, which includes implications for electroweak physics, neutrino masses and mixings, and lepton flavor changing processes such as $\ell_i \to \ell_j \gamma$. We also briefly discuss the direct detection of the dark matter in the model.

1. Introduction

Three of the important puzzles in cosmology relate to the origin of baryon asymmetry in the Universe, the nature of dark matter and the cosmic coincidence. Thus the visible universe exhibits an excess of baryons over anti-baryons and this excess is often displayed as the baryon number density to the entropy density ratio [1]

$$B/s \sim 6 \times 10^{-10}. \tag{1}$$

The basic tenets of how to generate baryon (lepton) excess has been known since the work of Sakharov [2], and consist of three conditions, i.e., the existence of baryon (or lepton) number violation, the presence of C and CP violating interactions, and out of equilibrium processes. In the standard model the ratio B/s is computed to be too small to fit observation pointing to the existence of beyond the standard model physics. Standard model also does not provide us with a candidate for dark matter and the astrophysical evidence for its presence again points to the existence of new physics beyond the standard model. Additionally one has the cosmic coincidence puzzle, i.e., the fact that the amount of dark matter and the amount of visible matter in the Universe are comparable. Specifically one has [3]

$$\frac{\Omega_{\rm DM} h_0^2}{\Omega_{\rm B} h_0^2} \approx 5.5. \tag{2}$$

The comparable sizes of the amounts of dark matter and of visible matter point to the possibility of a common origin of the two. This can be explained by the so-called asymmetric dark matter hypothesis where the dark particles are in thermal equilibrium with the standard model particles or with the particles of the minimal supersymmetric standard model in the early universe, and thus their chemical potentials are of the same order. The satisfaction of Eq. (2) then occurs via a constraint on the dark matter mass (for a sample of recent works see [4,5] and for reviews see [6]). Alternative schemes where dark matter carrying a lepton number (or a baryon number) is created first and a portion of it subsequently transfer to the visible sector have been considered in [7,8].

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Cogenesis of baryon/lepton asymmetry and the asymmetric dark matter have also been discussed recently in [9].

An important constraint on model building is the requirement that dark matter be stable, i.e., the dark particles does not decay into lighter standard model particles. In this work we consider an extension of the standard model and of the minimal supersymmetric standard model where the dark fields are charged under a $U(1)_x$ gauge symmetry while the standard model fields are neutral under $U(1)_x$, which forbids dark particles decay into the standard model particles and thus guarantees the stability of the dark matter. Additionally, the asymmetry of the dark particles generated in the early universe will not be washed out by Majorana mass terms since they are forbidden by the $U(1)_x$ gauge symmetry.[1] In the supersymmetric case, a gauged $U(1)_{B-L}$ model is also discussed.

Most conventional models of baryogenesis or leptogenesis assume that the fundamental vertices violate either baryon number or lepton number or both in conformity with the first Sakharov condition [11,12]. However, in this work we consider leptogenesis where the fundamental interactions conserve lepton number and leptogenesis consists in generating equal and opposite lepton numbers in the visible and in the dark sectors. Subsequently the sphaleron processes transmute a part of the leptons into baryons. The total $B–L$ in the universe is exactly conserved. This mechanism bypasses the difficulty in the GUT baryogenesis where a vanishing total $B–L$ implies that the baryon asymmetry generated would be washed out by the sphaleron interactions. While this idea has been recently pursued by several authors [13,14], our analysis differs significantly in structure and in content from previous works [13,14].[2] A more detailed comparison with these works is given at the end of Section 4. Earlier works on Dirac leptogenesis [16] can also generate the asymmetry in the visible sector starting from a $B–L$ vanishing universe. Due to the tiny Yukawa coupling, right-handed (Dirac) neutrinos would not be in thermal equilibrium with left-handed neutrinos, hence the sphaleron interactions which operate only on $SU(2)$ fields, will not wash out the lepton number stored in the right-handed neutrinos and thus the asymmetry is created.

The outline of the rest of the Letter is as follows: In Section 2 we discuss leptogenesis and the generation of asymmetric dark matter in a non-supersymmetric model where the vertices have no lepton number violation. The dark matter consists of two fermionic fields which carry the same lepton numbers but opposite $U(1)_x$ charges. Here we also compute the mass of the dark particles which satisfy the cosmic coincidence of Eq. (2). In Section 3 we extend the analysis to the supersymmetric case. The main difference in the analysis of Section 3 from the analysis of Section 2 is that in the supersymmetric case there are more species of dark matter particles. Specifically we have four types of fermionic particles and their bosonic super-partners which carry different combinations of the lepton numbers and $U(1)_x$ charges. We also discuss the possibility that $U(1)_x$ is $U(1)_{B-L}$. In Section 4 we discuss the phenomenology related to these models. Conclusions are given in Section 5.

[1] Models which allow a Majorana term for dark matter can undergo oscillations where the dark particle oscillates to its anti-particle. Such processes over the lifetime of the universe can produce symmetric dark matter which can lead to pair annihilation and wipe out the asymmetric dark matter [10].

[2] Baryogenesis with a gauged $U(1)_B$ symmetry is discussed in [15], where the dark sector and the visible sector carry the opposite baryon number and the total baryon number in the universe is conserved. While in this work a pre-existing excess of lepton number has been assumed, thus the total $B–L$ in the universe is not vanishing.

2. Non-supersymmetric model

We begin by considering the set of fields N_i, ψ, ϕ, X, X' with lepton number assignments $(0, +1, -1, +1/2, +1/2)$. Here N_i $(i \geqslant 2)$ are Majorana fermions, ψ, X, X' are Dirac fields and ϕ is a complex scalar field. The fields N_i, ψ, ϕ are heavy and will decay into lighter fields and eventually disappear and there would be no vestige left of them in the current universe. The dark sector is constituted of two fermionic fields X, X', which as indicated above each carry a lepton number $+1/2$ and are oppositely charged under the dark sector gauge group $U(1)_x$ with gauge charges $(+1, -1)$. All other fields are neutral under $U(1)_x$. We assume their interactions to have the following form which conserve both the lepton number and the $U(1)_x$ gauge symmetry:

$$\mathcal{L} = \lambda_i \bar{N}_i \psi \phi + \beta \bar{\psi} L H + \gamma \phi \bar{X}^c X' + h.c., \tag{3}$$

where the couplings λ_i are assumed to be complex and the couplings β, γ are assumed to be real. In addition we add mass terms so that

$$-\mathcal{L}_m = M_i \bar{N}_i N_i + m_1 \bar{\psi} \psi + m_2^2 \phi^* \phi + m_X \bar{X} X + m_{X'} \bar{X}' X'. \tag{4}$$

Here N_i have Majorana masses, while ψ, X, X' have Dirac masses. We assume the mass hierarchy $M_i \gg m_1 + m_2$, $m_1 \sim m_2 \gg m_X + m_{X'}$. We will see later that $m_X, m_{X'}$ are around 1 GeV. Consistent with the above constraint, m_1, m_2 which are the masses of ψ and ϕ respectively, could span a wide range from order of TeV to much higher scales.

In the early universe, the out-of-equilibrium decays of the heavy Majorana fields N_i produce a heavy Dirac field ψ and a heavy complex scalar field ϕ. The CP violation due to the complex couplings λ_i generates an excess of ψ, ϕ over their anti-particles $\bar{\psi}, \phi^*$ which carry the opposite lepton numbers. Since the lepton number carried by ψ and ϕ always sums up to zero, the out-of-equilibrium decays of N_i do not generate an excess of lepton number in the universe. Further, ψ and ϕ (as well as their anti-particles) produced in the decay of the Majorana fields N_i will sequentially decay, with ψ (and its anti-particle) decaying into the visible sector fields and ϕ (and its anti-particle) decaying into the dark sector fields. Their decays thus produce a net lepton asymmetry in the visible sector and a lepton asymmetry of opposite sign in the dark sector. We note that the absence of the decays $\psi \to \bar{X} + X'$ and $\phi^* \to L + H$ guarantees that leptonic asymmetries of equal and opposite sign are generated in the visible and in the dark sectors. Indeed, right after the heavy Majorana fermions N_i have decayed completely, and created the excess of ψ, ϕ over $\bar{\psi}, \phi^*$, equal and opposite lepton numbers are already assigned to the visible sector and the dark sector. It is clear from the above analysis that there is no violation of lepton number in the entire process of generating the leptonic asymmetries. We further note that while sphaleron interactions are active during the period when the leptogenesis and the genesis of (asymmetric) dark matter occur, they are not responsible for creating a net $B–L$ number in the visible sector, though they do play a role in transmuting a part of the lepton number into baryon number in the visible sector.

As will be discussed in Section 4, the symmetric component of dark matter would be sufficiently depleted by annihilating via a Z' pole into standard model particles, which ensures the asymmetric dark matter to be the dominant component of the current dark matter relic abundance. One can estimate on general grounds the mass of the dark particles in this model for the cosmic coincidence to occur. Since the total $B–L$ in the universe vanishes, the $B–L$ number in the visible sector is equal in magnitude and opposite in sign to the lepton number created in the visible sector right after