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Non-thermal WIMP baryogenesis

Ki-Young Choi [a], Sin Kyu Kang [b], Jongkuk Kim [a,*]

[a] Department of Physics, BK21 Physics Research Division, Institute of Basic Science, Sungkyunkwan University, Suwon 440-746, South Korea
[b] School of Liberal Arts, Seoul-Tech, Seoul 139-743, South Korea

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ABSTRACT

We propose a model of baryogenesis achieved by the annihilation of non-thermally produced WIMPs from decay of heavy particles, which can result in low reheating temperature. Dark matter (DM) can be produced non-thermally during a reheating period created by the decay of long-lived heavy particle, and subsequently re-annihilate to lighter particles even after the thermal freeze-out. The re-annihilation of DM provides the observed baryon asymmetry as well as the correct relic density of DM. We investigate how washout effects can affect the generation of the baryon asymmetry and study a model suppressing them. In this scenario, we find that DM can be heavy enough and its annihilation cross section can also be larger than that adopted in the usual thermal WIMP baryogenesis.

1. Introduction

The baryon density at present inferred from Cosmic Microwave Background (CMB) anisotropy and Big Bang Nucleosynthesis (BBN) is [1]

$$\Omega_B h^2 = 0.0223 \pm 0.0002, \tag{1}$$

which corresponds to the baryon asymmetry

$$Y_B \equiv \frac{n_B}{s} \simeq 0.86 \times 10^{-10}, \tag{2}$$

where n_B and s is the baryon number density and entropy density respectively. There are many suggested models for baryogenesis. One of them is the thermal weakly interacting massive particle (WIMP) baryogenesis [2–5], which has been paid much attention for past few years thanks to the intriguing coincidence of the observed baryon and dark matter (DM) abundances, $\Omega_B \simeq 5\Omega_{DM}$. WIMP miraculously accounts for Ω_{DM}, and may play a role in generation of baryon asymmetry. The WIMP baryogenesis mechanism [4] uses the WIMP dark matter annihilation during thermal freeze-out. Baryogenesis is successfully achieved because the WIMP annihilations violate baryon number, C and CP, and the out-of-equilibrium is attained when the DM number density is deviated from the thermal equilibrium. For this scenario to be effective, the temperature of the Universe must be larger than the freeze-out temperature of DM which is $T_{\rm fr} \simeq m_\chi/20$. Therefore there is a limitation for low-reheating temperature.

In new physics beyond the standard model (SM), there are many long-lived massive particles (we call it ϕ afterwards) that can dominate the energy density of the Universe, and decay, such as inflaton, moduli, gravitino, axino, curvaton, and etc [6]. These particles interact very weakly with visible sector and thus decay very late in the Universe. The lifetime can be longer than 10^{-7} sec which corresponds to the cosmic temperature around 1 GeV, which is far after the electroweak phase transition and freeze-out of WIMP DM with mass $m_\chi \sim \mathcal{O}(\text{TeV})$, whose freeze-out temperature is around $m_\chi/20$. Then, in the models with such a long-lived particle, the reheating temperature can be low enough. However, with such a low-reheating temperature, the relic abundance of DM can not be explained in simple models for thermal WIMP freeze-out. In addition, it is questionable whether baryon asymmetry can be successfully generated in models with low-reheating temperature.

Since the primodial asymmetry generated is diluted during the late time reheating, new generation of asymmetry is required. At the low temperature below the electroweak scale, leptogenesis does not work since the conversion of lepton asymmetry to baryon asymmetry via Shpaleron processes is effective at temperatures above the electroweak scale. Thus, alternative to leptogenesis is demanded to generate baryon asymmetry in models with low-reheating temperature. A direct generation of baryon asymmetry [7] may be possible without the help of Sphaleron processes.

* Corresponding author.
E-mail addresses: kiyoungchoi@skku.edu (K.-Y. Choi), skkang@snut.ac.kr (S.K. Kang), jongkukkim@skku.edu (J. Kim).

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The aim of this letter is to propose a possible way to generate baryon asymmetry applicable to models with low reheating temperature. We will show that DM can be produced from heavy long-lived unstable particles and then both baryon and DM abundances can be achieved by the re-annihilation of DM. While the SM particles produced from the decay of ϕ are thermalized quickly and find themselves in the thermal equilibrium, the interactions of DM are so slow that can stay in the out-of-equilibrium state until their re-annihilation. After re-annihilation, the dark matter relic density is fixed [8–14]. As will be shown later, in this scenario, Sakharov conditions [15] are satisfied with the violations of C and CP as well as B number during the re-annihilation of the non-thermal WIMP DMs[1] which are out-of-equilibrium.

This letter is organized as follows. In Section 2, we show how non-thermal WIMP can generate baryon asymmetry. Numerical results are presented in Section 3. A simple model to successfully achieve non-thermal WIMP baryogenesis is provided in Section 4. We discuss how washout can be suppressed before the baryon asymmetry is generated. Conclusions are given in Section 5.

2. Non-thermal WIMP baryogenesis

We begin by considering a long-lived heavy particle, ϕ, so that the corresponding reheating temperature is relatively low. Using a sudden-decay approximation, the relation between the reheating temperature and the lifetime, τ_ϕ, is roughly given by

$$T_{\rm reh} \simeq \left(\frac{90}{\pi^2 g_*}\right)^{1/4} \sqrt{M_{\rm P}\Gamma_\phi} \simeq 2.5\,{\rm GeV} \times \left(\frac{10^{-7}\,{\rm sec}}{\tau_\phi}\right)^{1/2}, \quad (3)$$

where we used the decay width $\Gamma_\phi = \tau_\phi^{-1}$. For a heavy scalar particle whose interactions to SM particles are suppressed by a certain high scale Λ, its decay rate and lifetime are roughly given by

$$\Gamma_\phi \sim \frac{1}{64\pi}\frac{m_\phi^3}{\Lambda^2}, \quad \text{and} \quad \tau_\phi \sim 10^{-7}\,{\rm sec}\left(\frac{1\,{\rm TeV}}{m_\phi}\right)^3 \left(\frac{\Lambda}{10^{12}\,{\rm GeV}}\right)^2, \quad (4)$$

respectively. Therefore in the following we will focus on the case of $m_\phi \simeq \mathcal{O}(\text{TeV})$ with $\Lambda = 10^{12}$ GeV, which gives a reheating temperature lower than the WIMP freeze-out temperature.

The decay of ϕ is continuous and even before reaching the lifetime, i.e. when $t \ll \tau_\phi$, the relativistic particles and DMs are produced continuously. Right after the production, they are non-thermal with the energy of $E \sim m_\phi/2$. The SM particles which have gauge interactions and large Yukawa couplings scatter efficiently and quickly settle down to the thermal equilibrium with corresponding temperature T, defined by

$$\rho_r = \frac{\pi^2}{30} g_* T^4, \quad (5)$$

where ρ_r is the energy density of the relativistic particles in the thermal equilibrium with the effective degrees of freedom g_*. However for DMs which have weak interactions, their scatterings are relatively slow and do not lead to the thermal equilibrium quickly. Instead they stay in the out-of-equilibrium until the re-annihilation happens efficiently. There is a thermal component of DM which is produced from the thermal plasma, and its number density follows equilibrium and then becomes frozen at around $T_{\rm fr} \simeq m_\chi/20$. However, the component are soon dominated by the non-thermal DM.

Even though $T_{\rm reh} \ll T_{\rm fr}$ and thermally produced dark matters are already frozen, the non-thermal DMs can re-annihilate again into light particles, when their number density is large enough to satisfy

$$n_\chi \langle \sigma_{\rm A} v\rangle > H, \quad (6)$$

where $\langle \sigma_{\rm A} v\rangle \sim \sigma_A$ is the total annihilation cross section of non-thermal DM arising from the decay of ϕ, which is relativistic with energy $m_\phi/2$.[2] The Hubble parameter H is given by the total sum of the energy density in the Universe as

$$H^2 = \frac{1}{3M_{\rm P}^2}(\rho_\phi + \rho_r + \rho_\chi), \quad (7)$$

where ρ_χ is the energy density of DM.

The Boltzmann equations which govern the evolution are written as

$$\dot\rho_\phi + 3H\rho_\phi = -\Gamma_\phi\rho_\phi\,, \quad (8)$$

$$\dot\rho_r + 4H\rho_r = (1-f_\chi)\Gamma_\phi\rho_\phi + 2\langle\sigma_A v\rangle\left(\frac{m_\phi}{2}\right) n_\chi n_{\bar\chi}\,, \quad (9)$$

$$\dot n_\chi + 3Hn_\chi = f_\chi\Gamma_\phi\frac{\rho_\phi}{m_\phi} - \langle\sigma_A v\rangle(n_\chi n_{\bar\chi} - n_\chi^{\rm eq} n_{\bar\chi}^{\rm eq})\,, \quad (10)$$

$$\dot n_{\bar\chi} + 3Hn_{\bar\chi} = f_\chi\Gamma_\phi\frac{\rho_\phi}{m_\phi} - \langle\sigma_A v\rangle(n_\chi n_{\bar\chi} - n_\chi^{\rm eq} n_{\bar\chi}^{\rm eq})\,, \quad (11)$$

where f_χ is the branching ratio of ϕ decay to DM, e.g. $\phi \to \chi + \bar\chi$.

When the decay is the dominant source, the approximate scaling solutions for ϕ and the radiation are given by

$$\rho_\phi = \rho_{\phi,i}\left(\frac{a_i}{a}\right)^3 e^{-\Gamma_\phi t}, \qquad \rho_r \simeq \frac{2}{5}\frac{(1-f_\chi)\Gamma_\phi}{H}\rho_\phi \propto a^{-3/2}. \quad (12)$$

For DMs, they follow the thermal equilibrium initially and soon freeze out settling into the quasi-stable state where the production from decay and the annihilation equals to each other. At this epoch, the scaling solutions are given by

$$n_\chi \simeq n_{\bar\chi} \simeq \left(\frac{f_\chi\Gamma_\phi\rho_\phi}{\langle\sigma_A v\rangle m_\phi}\right)^{1/2} \propto a^{-3/2}. \quad (13)$$

After reheating, when there is no more production of non-thermal DM, the DM annihilation is efficient and the final abundance is rearranged as [11]

$$Y_\chi \equiv \frac{n_\chi}{s} \simeq \frac{H(T_{\rm reh})}{\langle\sigma_{\rm A} v\rangle s} \simeq \frac{1}{4}\left(\frac{90}{\pi^2 g_*}\right)^{1/2}\frac{1}{\langle\sigma_{\rm A} v\rangle M_{\rm P} T_{\rm reh}}, \quad (14)$$

and the corresponding relic density of DM is

$$\Omega_\chi h^2 \simeq 0.14\left(\frac{90}{\pi^2 g_*}\right)^{1/2}\left(\frac{m_\chi}{1\,{\rm TeV}}\right)\left(\frac{10^{-8}\,{\rm GeV}^{-2}}{\langle\sigma_{\rm A} v\rangle}\right)\left(\frac{20\,{\rm GeV}}{T_{\rm reh}}\right). \quad (15)$$

[1] A leptogenesis at the reheating era was considered [16,17]. Here they consider the SM particles from the inflaton decay are out-of equilibrium until the thermalization. During the scattering process, the asymmetry is generated in the SM sector.

[2] For complete calculations, we need to keep track of the momentum dependence of the DM distribution function [18]. However, its effect is expected to be not so substantial to change our main results. In our scenario, we restrict ourselves to $m_\chi \sim m_\phi$, in which case the thermally averaged cross section of DM is similar to the non-thermall averaged one.