Non-thermal WIMP baryogenesis

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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 wafruit 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.

Keywords: Baryogenesis, dark matter, early Universe

1. Introduction

The baryon density at present inferred from Cosmic Microwave Background (CMB) anisotropy and Big Bang Nucleosynthesis (BBN) is \[ \Omega_B h^2 = 0.0223 \pm 0.0002, \] (1)
which corresponds to the baryon asymmetry
\[ Y_B \equiv \frac{n_B}{s} \approx 0.86 \times 10^{-10}, \] (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 \cite{2,3,4,5}, which has been paid much attention for past few years thanks to the intriguing coincidence of the observed baryon and dark matter (DM) abundances, \( \Omega_B \equiv \frac{5}{3} \Omega_{DM} \). WIMP miraculously accounts for \( \Omega_{DM} \), and may play a role in generation of baryon asymmetry. The WIMP baryogenesis mechanism \cite{4} uses the WIMP dark matter annihilation during thermal freeze-out. Baryogenesis is successfully achieved because the WIMP annihilation 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 \( T_{\phi} \approx m_\phi/20 \). 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 \( \phi \) afterwards) that can dominate the energy density of the Universe, and decay, such as inflaton, moduli, gravitino, axino, curvaton, and etc \cite{6}. These particles interact very weakly with visible sector and thus decay very late in the Universe. The lifetime can be longer than \( 10^{27} \) 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 \( m_\phi \sim O(\text{TeV}) \), whose freeze-out temperature is around \( m_\phi/20 \). 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 primordial 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 Shapleron 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 \cite{7} may be possible without the help of Shapleron processes.

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 \( \phi \) 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 \cite{8,9,10,11}.
As will be shown later, in this scenario, Sakharov conditions are satisfied with the violations of C and CP as well as B number during the re-annihilation of the non-thermal WIMP DMs 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, \( \phi \), so that the corresponding reheating temperature is relatively low. Using a sudden-decay approximation, the relation between the reheating temperature and the lifetime, \( \tau_\phi \), is roughly given by

\[
T_{\text{reh}} \approx \left( \frac{90}{\pi^4 g_*} \right)^{1/4} \sqrt{M_\phi \Gamma_\phi} \approx 2.5 \text{ GeV} \times \left( \frac{10^{-7} \text{ sec}}{\tau_\phi} \right)^{1/2},
\]

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

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

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

The decay of \( \phi \) 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

\[
\rho_r = \frac{\pi^2}{30} g_* T^4,
\]

where \( \rho_r \) 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 \( T_{\text{re}} \approx m_\phi/20 \). However, the component are soon dominated by the non-thermal DM.

Even though \( T_{\text{reh}} \ll T_{\text{re}} \) 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

\[
n_\chi \langle \sigma_\chi v \rangle > H, \tag{6}
\]

where \( \langle \sigma_\chi v \rangle \sim \sigma_A \) is the total annihilation cross section of non-thermal DM arising from the decay of \( \phi \), which is relativistic with energy \( m_\phi/2. \) The Hubble parameter \( H \) is given by the total sum of the energy density in the Universe as

\[
H^2 = \frac{1}{3 M_P^2} (\rho_\phi + \rho_r + \rho_\chi), \tag{7}
\]

where \( \rho_\chi \) is the energy density of DM.

The Boltzmann equations which govern the evolution are written as

\[
\dot{\rho}_\phi + 3H \rho_\phi = -\Gamma_\phi \rho_\phi, \tag{8}
\]

\[
\dot{\rho}_r + 4H \rho_r = (1 - f_\chi) \Gamma_\phi \rho_\phi + 2 \langle \sigma_\chi A \rangle \frac{m_\phi}{2} n_\chi n_\bar{\chi}, \tag{9}
\]

\[
\dot{n}_\chi + 3H n_\chi = f_\chi \Gamma_\phi \rho_\phi - \langle \sigma_\chi A \rangle (n_\chi n_\bar{\chi} - n_\bar{\chi} n_\chi^*) + \rho_\chi, \tag{10}
\]

\[
\dot{n}_\bar{\chi} + 3H n_\bar{\chi} = f_\chi \Gamma_\phi \rho_\phi - \langle \sigma_\chi A \rangle (n_\chi n_\bar{\chi} - n_\bar{\chi} n_\chi^*), \tag{11}
\]

where \( f_\chi \) is the branching ratio of \( \phi \) decay to DM, e.g. \( \phi \rightarrow \chi + \bar{\chi} \).

When the decay is the dominant source, the approximate scaling solutions for \( \phi \) and the radiation are given by

\[
\rho_\phi = \rho_\phi^0 \left( \frac{a(t)}{a_0} \right)^{-3/2},
\]

\[
\rho_r = \frac{2}{5} \left( 1 - f_\chi \right) \frac{\Gamma_\phi}{H} \rho_\phi^0 \propto a^{-3/2}. \tag{12}
\]

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

\[
n_\chi \propto n_\bar{\chi} \approx \left( \frac{f_\chi \Gamma_\phi \rho_\phi}{\langle \sigma_\chi A \rangle m_\phi} \right)^{1/2} \propto a^{-3/2}. \tag{13}
\]

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

\[
Y_\chi \equiv \frac{n_\chi}{s} = \frac{H(T_{\text{reh}})}{\langle \sigma_\chi A \rangle s} \approx \frac{1}{4} \left( \frac{90}{\pi^4 g_*} \right)^{1/2} \frac{1}{\langle \sigma_\chi A \rangle M_P T_{\text{reh}}}, \tag{14}
\]

For complete calculations, we need to keep track of the momentum dependence of the DM distribution function. However, its effect is expected to be not so substantial to change our main results. In our scenario, we restrict ourselves to \( m_\phi - m_\chi \), in which case the thermally averaged cross section of DM is similar to the non-thermall averaged one.
baryogenesis, however, the washout term must be suppressed. 

\[ \sigma_{\text{washout}} \langle \chi \chi \rightarrow \cdots \rangle \approx \langle \sigma_{\text{washout}} \rangle n_B n_{\text{eq}} \langle \psi \rangle \]

where we have used Eq. (13) and the corresponding relic density of DM is

\[ \Omega_X h^2 = 0.14 \left( \frac{90}{20} \right)^{1/2} \left( \frac{m_X}{1 \text{ TeV}} \right) \left( \frac{10^{-8} \text{ GeV}^{-2}}{\langle \sigma_{\chi \chi} v \rangle} \right) \left( \frac{20 \text{ GeV}}{T_{\text{reh}}} \right), \]

(15)

Since the non-thermal DMs are out of equilibrium, a baryon asymmetry can be generated during the re-annihilation of DMs. The CP asymmetry, \( \epsilon \), generated via the B number violating annihilation cross sections of DM.

\[ \epsilon = \frac{\langle \sigma_{\chi \chi} \rangle (\chi \chi \rightarrow \cdots) - \langle \sigma_{\chi \chi} \rangle (\bar{\chi} \bar{\chi} \rightarrow \cdots)}{\langle \sigma_{\chi \chi} \rangle (\bar{\chi} \bar{\chi} \rightarrow \cdots) + \langle \sigma_{\chi \chi} \rangle (\chi \chi \rightarrow \cdots)}, \]

(16)

where \( \langle \sigma_{\chi \chi} \rangle (\chi \chi \rightarrow \cdots) \) and \( \langle \sigma_{\chi \chi} \rangle (\bar{\chi} \bar{\chi} \rightarrow \cdots) \) are the B number violating annihilation cross sections of DM.

Then the Boltzmann equation for the baryon asymmetry \( n_B \) is given by

\[ \dot{n}_B + 3Hn_B = \epsilon \langle \sigma_{\chi \chi} \rangle (n_B^2 - n_{\text{eq}}^2) - \langle \sigma_{\text{washout}} \rangle n_B n_{\text{eq}}, \]

(17)

where \( \langle \sigma_{\chi \chi} \rangle \) is the total B number violating annihilation cross section of DM,

\[ \langle \sigma_{\chi \chi} \rangle = \langle \sigma_{\chi \chi} \rangle (\chi \chi \rightarrow \cdots) + \langle \sigma_{\chi \chi} \rangle (\bar{\chi} \bar{\chi} \rightarrow \cdots), \]

(18)

which can be comparable to or smaller than the total annihilation of DM, \( \langle \sigma_{\chi \chi} \rangle \lesssim \langle \sigma_{\chi \chi} \rangle \). The last term in Eq. (17) is the washout effect, which is expected to be the same order as the B number violating interaction, \( \langle \sigma_{\text{washout}} \rangle \sim \langle \sigma_{\chi \chi} \rangle \). For successful baryogenesis, however, the washout term must be suppressed.

The washout term can be suppressed in the case that

\[ \frac{\langle \sigma_{\text{washout}} \rangle m_B n_{\text{eq}}}{\epsilon \langle \sigma_{\chi \chi} \rangle n^2_{\text{eq}}} \ll 1. \]

(19)

This condition is satisfied when \( n_B n_{\text{eq}} \ll n^2_{\text{eq}} \) and/or \( \langle \sigma_{\text{washout}} \rangle \ll \langle \sigma_{\chi \chi} \rangle \). The former can be achieved when one of the final particles, denoted by \( \psi \) with mass \( m_{\psi} \), produced from the B number violating annihilation of DM is non-relativistic while keeping in thermal equilibrium and thus its number density, \( n_{\psi} \), is exponentially suppressed as \( e^{-m_{\psi}/T} \).

During the matter-dominated era by \( \phi \), when ignored the washout effect, we can find the scaling solution for the baryon number density as

\[ n_B = \epsilon \langle \sigma_{\chi \chi} \rangle n_B^2 \frac{2}{3H} = \frac{2\epsilon f_i \Gamma_P M_P}{\sqrt{3} m_{\phi}} \langle \sigma_{\chi \chi} \rangle \rho_{\phi} \langle \sigma_{\chi \chi} \rangle^{1/2} \propto a^{-3/2}, \]

(20)

where we have used Eq. (13) and \( t = 2/3H \) during matter-domination.

Now let us estimate the baryon asymmetry created in our scenario in the sudden decay approximation. After reheating, the number density of the non-thermal DM is

\[ n_X = f_X n_{\phi} = f_X \rho_{\phi} / m_{\phi}, \]

(21)

with the number density of \( \phi, n_{\phi} = \rho_{\phi} / m_{\phi} \). The DM re-annihilation can happen when the WIMP annihilation cross section satisfies the condition,

\[ f_X \langle \sigma_{\chi \chi} \rangle > \frac{m_{\phi}}{3 M_P T_{\text{reh}}^2} \left( \frac{90}{20} \right)^{1/2}, \]

(22)

from Eq. (6). Therefore the baryon asymmetry is estimated as

\[ Y_B \sim \frac{\epsilon}{\langle \sigma_{\chi \chi} \rangle} \frac{\langle \sigma_{\chi \chi} \rangle n_X}{\langle \sigma_{\chi \chi} \rangle} Y = \epsilon f_X \frac{\langle \sigma_{\chi \chi} \rangle n_X}{\langle \sigma_{\chi \chi} \rangle} \left( \frac{T_{\text{reh}} / m_{\phi}}{10^{-3}} \right), \]

(23)

where \( Y \equiv n/s \) with the entropy density \( s = (2n^2/45g_{s,S})T^3 \) and effective entropy degrees of freedom \( g_{s,S} \). In the second line in Eq. (23), we have used

\[ \frac{n_{\phi}}{s} = \frac{3 T_{\text{reh}}}{4 m_{\phi}} \]

(24)
3. Numerical Results

In the left panel of Fig. 1, we show how the background energy density of φ and the radiation evolve along with \(x = m_x/T\) (or \(a/a_i\)) for \(T_{\text{reh}} = 20\) GeV, \(m_x = 2\) TeV, and \(m_\phi = 5\) TeV. We can see that the reheating happens at around \(x \approx 100\) (or \(a/a_i \approx 10^3\)) and the energy density of the radiation shows the scaling behavior decreasing proportional to \(a^{-3/2}\) before reheating and to \(a^{-3}\) after reheating, as shown in the Eq. (12).

In the right panel of Fig. 1 we plot \(Y_x\) and \(Y_\phi\) for \(\langle \sigma \phi_v \rangle \approx 10^{-7}\) (solid line), \(10^{-8}\) (dashed line), and \(10^{-9}\) (dotted line) GeV\(^{-2}\). We take \(\epsilon = 0.001\) and \(f_\chi = 0.01\) as inputs, and the ratio, \(\langle \sigma \phi_v \rangle / \langle \sigma \phi_A \rangle\), is fixed to be \(5 \times 10^{-3}\). Note that DMs are in the thermal equilibrium initially and frozen and soon become dominated by the non-thermal components produced from the decay of \(\phi\) at around \(a/a_i \approx 10^3\) corresponding to \(x = m_x/T \approx 20\). During this period, the abundance \(Y_x\) scales as

\[
Y_x = \frac{n_x + n_\chi}{s} \propto \frac{\langle \sigma \phi_v \rangle}{T^3} \propto a^{-3/2},
\]

where we have used Eq. (13) and adopted \(T \propto a^{-3/2}\) during matter domination. This scaling can be seen in the right panel of Fig. 1. The abundance of DM in the scaling regime depends on \(\langle \sigma \phi_A \rangle^{-1/2}\) as in Eq. (13), however after reheating, the DMs re-annihilate quickly and the final relic density is inversely proportional to \(\langle \sigma \phi_v \rangle\) as in Eq. (14).

As mentioned above, baryon asymmetry can be generated from the annihilation of WIMP DM when DM begins to deviate from the equilibrium and washout effect freezes out, that is called (thermal) WIMPy baryogenesis [4, 19, 20]. However, during matter-dominated era, the baryon asymmetry is soon dominated by that generated from the annihilation of non-thermal DM. During this period, the baryon asymmetry also shows the scaling behavior as in Eq. (20). In the right panel of Fig. 1 the abundance of baryon asymmetry, \(Y_B\), appears independent of \(\langle \sigma \phi_v \rangle\) because the ratio \(\langle \sigma \phi_v \rangle / \langle \sigma \phi_A \rangle\) is fixed in this figure, as can be seen in Eq. (20). We can see from the figure that the required value for the baryon asymmetry \(Y_B \sim 10^{-10}\) given in Eq. (4) can be easily obtained. Here we used \(m_\phi = 3\) TeV to suppress the wash-out effect. The dependence of \(Y_B\) on \(m_\phi\) will be presented in Fig. 3.

In Fig. 2 we show the evolution of \(Y_x\) and \(Y_\phi\) for different values of \(\langle \sigma \phi_v \rangle\) (left panel) and \(f_\chi\) (right panel). We take \(\langle \sigma \phi_v \rangle \approx 10^{-9}\) (solid line), \(10^{-10}\) (dashed line), and \(10^{-11}\) (dotted line) GeV\(^{-2}\) in the left panel and \(f_\chi = 0.01\) (solid line), \(10^{-5}\) (dashed line), and \(0\) (dotted line) in the right panel for the same inputs as in Fig. 1 except that we chose \(\langle \sigma \phi_A \rangle = 10^{-8}\) GeV\(^{-2}\) and \(\langle \sigma \phi_v \rangle = 0.005 \times \langle \sigma \phi_A \rangle\). One can easily see that the final \(Y_B\) is proportional to not only \(\langle \sigma \phi_v \rangle\) in the left panel, but also \(f_\chi\) in the right panel.

In the limit of \(f_\chi \to 0\), there is no DM production from the decay of heavier particle. However it does not simply lead to the result of thermal WIMP baryogenesis. Instead, the baryon asymmetry generated from the decay of \(\phi\) during the WIMP freeze-out is diluted due to the entropy generation. This can be seen in the right figure of Fig. 2. In this case with \(f_\chi = 0\), we find that \(Y_B \approx 10^{-16}\) and \(Y_x \approx 10^{-14}\), which is too small to explain baryogenesis and dark matter relic density simultaneously.

In Fig. 3 we show the effects of wash-out by changing the mass of a particle, \(\psi\), which is produced in the B-violating DM annihilation. Here we have used \(m_\psi = 3\) TeV (solid line), 1.5 TeV (dashed line), 300 GeV (dot-dashed line), 150 GeV (dotted line). We can clearly see from Fig. 3 that the wash-out is effective and thus \(Y_B\) is suppressed when \(T \gtrsim m_\psi\), but at lower temperatures \(T \lesssim m_\phi/25\) the wash-out is suppressed and thus \(Y_B\) can be sizable. For a given reheating temperature \(T_{\text{reh}} = 20\) GeV, the final \(Y_B\) is affected when \(m_\phi \lesssim 500\) GeV, which is roughly \(25T_{\text{reh}}\). Note that \(Y_x\) is independent of the washout effect.
4. A model suppressing washout

As a specific example for the suppression of washout effects, we adopt the model suggested in [2, 13, 14], where the DMs annihilate to quarks directly, and embed the non-thermal WIMP baryogenesis in the model. The model includes a vectorlike gauge singlet dark matter $X$ and $\bar{X}$, singlet pseudoscalars $S_a$, and vectorlike exotic quark color triplets $\psi_i$ and $\bar{\psi}_j$, with an interaction

$$\Delta L = \frac{i}{2}(A_{X,a}X^2 + A'_{X,a}X^2)S_a + i\lambda_{B1}S_a\bar{\psi}\psi.$$  \hspace{1cm} (26)

The DM annihilations occur through the intermediate $S$ states into $\bar{\psi}$ and $\psi$,

$$XX \rightarrow S^* \rightarrow \bar{\psi}\psi, \quad \text{and} \quad \bar{X}X \rightarrow S^* \rightarrow \bar{\psi}\psi.$$  \hspace{1cm} (27)

At the same time, we assume that there are DM annihilations that do not violate baryon number. A baryon asymmetry is generated in $\bar{\psi}$ as well as in $\psi$. Since we consider $\bar{\psi}$ is decoupled from the SM sector while in equilibrium with the hidden sector fields, the baryon asymmetry in the SM field is not eliminated. We assume that the reheating temperature is lower than the mass scale of $\bar{\psi}$, $T_{\text{reh}} \ll m_{\psi}$, so that the washout effect is suppressed thanks to the exponential suppression of the number density of $\psi$ as shown in Fig. 3.

The CP asymmetry is given by

$$\epsilon \approx \frac{1}{6\pi} \frac{\text{Im}(\lambda_B^1\lambda_B^1)}{|\lambda_B^1|^2}$$  \hspace{1cm} (28)

where we assumed that $m_\phi \gg m_{\psi}$. For the couplings $\lambda_X^1 = 1$ and $\lambda_{B1} = \lambda_{B2} = 0.1$, the CP asymmetry given by Eq. (28) is around $\epsilon \sim 2.5 \times 10^{-4}$ in the case of the maximal CP violating phase. The $B$ violating DM annihilation cross section is estimated as $\sigma \sim (\lambda_X^1A_B^1)^2 \frac{1}{m_{\psi}^2}$.

In Fig. 4 we show the effects of the wash-out depending on $m_\psi$ for different model parameters, $A_B \equiv A_B^1 = A_B^2 = 1$ (solid line), 0.1 (dashed line), 0.01 (dotted line) and $\lambda_X^1 = 1$ for $T_{\text{reh}} = 20 \text{ GeV}$ and $m_\psi = 2 \text{ TeV}$. As can be seen here, the washout of $Y_B$ is sizable for $m_\psi \lesssim T_{\text{reh}}$, whereas that is ineffective for $m_\psi \gtrsim 500 \text{ GeV}$ which corresponds roughly to $25T_{\text{reh}}$. The horizontal line represents the required baryon asymmetry in Eq. (3).

In this model, since the particle $\psi$ has color charges, $m_\psi$ is strongly constrained by the collider searches. From the current LHC gluino search, it is inferred that the lower bounds on $m_\psi$ are $1.3 \text{ TeV} \sim 1.6 \text{ TeV}$ depending on neutralino mass [21]. The shaded region in Fig. 4 is disfavored by those bounds. For sufficient suppression of wash-out, we require that the reheating temperature is smaller than the thermal freeze-out temperature of DM, then we need $T_{\text{reh}} < m_\psi/25$. At the same time, if we assume that the reheating temperature is smaller than the thermal freeze-out temperature of DM, then we need $T_{\text{reh}} < m_\psi/25$.

The relic density of dark matter is determined as in Eq. (13) which depends on the total annihilation cross section of dark matter as well as the reheating temperature. For $T_{\text{reh}} = 20 \text{ GeV}$, and $m_\psi = 2 \text{ TeV}$, the right value of the DM relic density can be obtained with $\langle \sigma v \rangle \approx 5 \times 10^{-8} \text{ GeV}^{-2}$. This gives a testable window in the indirect detection of dark matter depending on the annihilation modes. If the dominant annihilation modes of dark matter is $b\bar{b}$ then it might be marginally possible to detect signals in the gamma-ray detection [22]. On the other hand, if the dominant annihilation is into the hidden sector, then it might be difficult to see signals through the indirect searches.

5. Conclusion

In this work, we have proposed a WIMP baryogenesis that can be reconciled with low reheating temperature. In this scenario, DM is non-thermally produced 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 have investigated how wakeout effects can affect the gener-
ation of the baryon asymmetry and studied a model suppressing them by introducing a heavy particle $\psi$, which is decoupled from the SM fields when it is produced. From the analysis, we have found that DM can be heavy enough and its annihilation cross section can also be larger than that adopted in the usual thermal WIMP baryogenesis.

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