Triplet Dark Matter from leptogenesis

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Abstract

A triplet dark matter candidate from thermal leptogenesis is considered with building a model. The model is based on the standard two Higgs doublet model and seesaw mechanism with Higgs triplets. The parameters (couplings and masses) are adjusted for the observed small neutrino mass and the leptogenesis. Dark matter particles can annihilate and decay in this model. The time evolution of the dark matter number is governed by (co)annihilations in the expanding universe, and its mass is constrained by the observed relic density. The dark matter can decay into final states with three leptons (two charged leptons and one neutrino). We investigate whether the decay in the galaxy can account for cosmic ray anomalies in the positron and electron spectrum. A noticeable point is that if the dark matter decays into each lepton with different branching ratios, cosmic ray anomalies in AMS-02 measurements of the positron fraction and the Fermi LAT measurements of the electrons-plus-positrons flux could be simultaneously accounted for from its decay products. The leptogenesis within this model is studied in an appendix.

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I. INTRODUCTION

Recent progress in cosmology and particle physics has eluded scientists for more exact science. The Planck released data with relatively good precision, and the standard model of particle physics has been tested by the discovery of a Higgs-like boson with a mass around 126 GeV in both the ATLAS and CMS experiments. Our current understanding of the universe is based on the Friedman-Robertson-Walker (FRW) model and the standard model (SM) of particle physics, called the standard cosmological model. Although we might understand most of the observations in the standard cosmological model, dark matter (DM) and baryon asymmetry in the universe (BAU) require new physics beyond the standard (cosmological) model.

The DM and the BAU have quite appealing scenarios. Dark matter as a thermal relic\footnote{The standard model tends to fail to realize the large observed asymmetry because the only CP asymmetry is through the complex phase in the Cabibbo-Kobayashi-Maskawa matrix and it is too small to explain the observed baryon asymmetry. Furthermore a first order electroweak phase transition is not plausible for Higgs mass with 126 GeV. Hence electroweak baryogenesis is practically ruled out.} is well motivated in the hot big bang model. DM particles would be in thermal equilibrium in the early universe and freeze out below its mass scale in the expanding universe. The observed relic density\footnote{The $\psi$ has three components $\{\psi^+, \psi^0, \psi^-\}$, and the neutral component is our DM candidate. Since other components are in the same set, the $\psi$ is called the triplet DM. In this paper, the symbol $\psi$ is also referred to as the DM unless otherwise noted.} can naturally be explained by the annihilation cross section provided its mass lies in the GeV-TeV range. The BAU may be explained if three conditions proposed by Sakharov\footnote{The $\psi$ has three components $\{\psi^+, \psi^0, \psi^-\}$, and the neutral component is our DM candidate. Since other components are in the same set, the $\psi$ is called the triplet DM. In this paper, the symbol $\psi$ is also referred to as the DM unless otherwise noted.} are satisfied, namely baryon number violation, C and CP violation and departure from thermal equilibrium in the early universe. The most appealing candidate to explain the BAU must be leptogenesis\footnote{The $\psi$ has three components $\{\psi^+, \psi^0, \psi^-\}$, and the neutral component is our DM candidate. Since other components are in the same set, the $\psi$ is called the triplet DM. In this paper, the symbol $\psi$ is also referred to as the DM unless otherwise noted.}. The lepton asymmetry may arise in the same dimension-five operator relevant to the neutrino mass. The sphaleron processes convert a part of the lepton number to the baryon number, and an excess of baryons can be explained.

In this paper, we utilize both properties with the additional particle content in the standard model gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$. A Majorana fermion triplet\footnote{The $\psi$ has three components $\{\psi^+, \psi^0, \psi^-\}$, and the neutral component is our DM candidate. Since other components are in the same set, the $\psi$ is called the triplet DM. In this paper, the symbol $\psi$ is also referred to as the DM unless otherwise noted.} $\psi$ with a $SU(2)_L$ weak charge is considered as a DM candidate with lifetime around $10^{26}$ sec. The seesaw mechanism with a heavy triplet scalar (Higgs triplet) $\chi$ is employed to generate the
neutrino mass \( \delta \) and the lepton asymmetry \( \alpha \) by lepton number violating interaction at the mass scale of \( \chi \). We consider the standard two Higgs doublet model (2HDM) as a low energy effective theory.

If our DM candidate is \( Z_2 \)-odd, it will couple to \( Z_2 \)-odd charged leptons with the Higgs triplet. It can thus decay into three body final states (two charged leptons and one neutral lepton) by a \( \chi \) exchange. Since the DM candidate has a weak charge, DM particles can also annihilate into SM particles. The time evolution of DM number is governed by (co)annihilations in the expanding universe, and its mass (\( \sim 2.7 \) TeV) is constrained by the observed relic density. The decay process is negligible to the DM number evolution and its lifetime is much longer than the age of the universe, 13.7 Gyr (= \( 4.3 \times 10^{17} \) sec) within the \( \Lambda \)CDM concordance model \( [7] \), the decay rate with lifetime around \( 10^{26} \) sec is much larger than annihilation rate at present. We examine whether cosmic ray anomalies in the positron spectrum can be accounted for by DM decay. The predictions in simple or single channels (democratic decay, \( \mu^+ \mu^- \nu \) dominant decay, \( \tau^+ \tau^- \nu \) dominant decay) could fit each experimental result of AMS-02 or Fermi LAT, but are unlikely to fit both experimental results together. We calibrate our prediction by providing different branching ratios into each channel. This method allows us to fit AMS-02 and Fermi LAT measurements simultaneously. There are several models to accommodate the decaying dark matter to account for the cosmic ray anomalies, dark matter in grand unification models \( [8–13] \), sterile neutrino dark matter \( [14, 15] \), gravitino dark matter \( [16–28] \), Goldstino dark matter \( [29, 30] \) and instanton-mediated dark matter \( [31] \).

The outline of this paper is as follows. In Sec. II we propose a model with a triplet fermion. The seesaw mechanism and the standard 2HDM are employed. In Sec. III we discuss the time evolution of the DM number density in the expanding universe. In Sec. IV, the cosmic ray anomalies in the positron spectrum are interpreted by DM decay. Finally, our conclusion is given in Sec. V. In Appendix, baryon asymmetry via leptogenesis is studied within this model.

II. THE MODEL DESCRIPTION

Our \( Z_2 \)-odd DM candidate \( \psi \) is completely stable in the SM. The only interaction is an annihilation into SM particles through the operator \( \bar{\psi} W \psi \). However, if we mind the
seesaw mechanism with at least a heavy Higgs triplet \( \chi \) for tiny neutrino mass, the DM candidate can have additional interactions in the standard 2HDM (\( Z_2 \) symmetric 2HDM). The standard 2HDM was built to avoid potentially large flavor changing neutral currents (FCNCs) with \( Z_2 \) symmetry, that is \( d^c, e^c \) and one Higgs doublet \( \phi_1 \) are \( Z_2 \)-odd, and \( u^c \) and the other Higgs doublet \( \phi_2 \) are \( Z_2 \)-even. Our \( Z_2 \)-odd DM candidate \( \psi \) is thus allowed to couple to \( Z_2 \)-odd charged leptons with the Higgs triplet \( \chi \). It can thus decay into three body final states by a \( \chi \) exchange. The relevant potential which can describe interactions with new particles is given by

\[
ig \bar{\psi} \gamma \psi + y_\ell Tr(\psi \chi \ell\ell) + \mu_1 \phi_1 \chi \ell + \mu_2 \phi_2 \chi \ell + h.c.,
\]

where flavor indices are suppressed. The symbol \( \ell \) stands for the left-handed lepton doublet, and the components of Higgs doublets are \( \{ \phi_{1,2}, \phi_{1,2}^0 \} \) with gauge charge \( (1, 2, -\frac{1}{2}) \) in the gauge group \( SU(3)_C \times SU(2)_L \times U(1)_Y \). The fermion triplet \( (1, 3, 0) \) and the Higgs triplet \( (1, 3, 1) \) were expressed in bilinear form,

\[
\psi \equiv \begin{pmatrix} \frac{1}{\sqrt{2}} \psi^0 & \psi^+ \\ \psi^- & -\frac{1}{\sqrt{2}} \psi^0 \end{pmatrix}, \chi \equiv \begin{pmatrix} \frac{1}{\sqrt{2}} \chi^+ & \chi^{++} \\ \chi^0 & -\frac{1}{\sqrt{2}} \chi^+ \end{pmatrix}.
\]

The second term describes the lepton number violating interaction by one unit (\( \Delta L = 1 \)). The third term does the lepton number violating interaction by two units (\( \Delta L = 2 \)). The rest of the terms are scalar cubic potentials.

In the low energy effective theory, the heavy scalar triplet is decoupled. It can be integrated out, and this handling gives rise to a sub-eV Majorana mass of neutrinos as required by oscillation experiments. The tiny neutrino mass can be generated by the combination of \( \Delta L = 2 \) and Higgs cubic potentials,

\[
m_\nu \approx y_\ell \frac{\mu_1 v_1^2 + \mu_2 v_2^2}{2 M_\chi^2},
\]

where \( M_\chi \) is the mass of Higgs triplet, and \( v_1/\sqrt{2}(v_2/\sqrt{2}) \) is the vacuum expectation value of \( \phi_1(\phi_2) \). This form is reduced to the usual standard form with \( v^2 = v_1^2 + v_2^2 \approx 246 \text{ GeV} \) for \( \mu_1 = \mu_2 \). The strongest upper limit on the mass of neutrinos comes from cosmology. The summed mass of the three neutrinos must be less than 0.23 eV from the analysis of cosmological data such as the cosmic microwave background radiation (CMB) and baryon
acoustic oscillations (BAO). On the other hand, there exists at least one neutrino mass eigenstate with a mass of at least 0.04 eV \[33\] from atmospheric neutrino oscillations. The mass scale of $\chi$ is of the order of $10^{10} - 10^{16}$ GeV, depending on the couplings $y_\ell$, $\mu_1$ and $\mu_2$. The lepton asymmetry may arise in the lepton number violating operators relevant to the neutrino mass ($\Delta L = 2$) and DM decay ($\Delta L = 1$). The details of lepton asymmetry in this model are studied in Appendix.

III. DARK MATTER ANNIHILATION AND RELIC DENSITY

In the expanding universe, the number density of DMs would decrease as long as the temperature remains higher than the DM mass. When the temperature dropped below the DM mass, the number density of DMs would drop exponentially (Boltzmann suppression). If equilibrium was maintained until today, there would be very few DMs left, but the DM number density would freeze out at some point and a substantial number of DMs would be left today. Detailed evolution of the Boltzmann equation is necessary for an accurate prediction. In our model, the DM can decay and annihilate. The time evolution Boltzmann equation of DM number density is given by

$$Y'(x) = -\frac{\Gamma}{xH} (Y - Y_{\text{eq}}) - \frac{s \langle \sigma_{\text{eff}} v \rangle}{xH} \left( Y^2 - Y_{\text{eq}}^2 \right)$$

where $x = M/T$ is the inverse temperature with DM mass $M$, $Y(Y_{\text{eq}})$ is the (equilibrium) number density in units of entropy density $s$, $H$ is the Hubble parameter, $\Gamma$ is the DM decay rate (width) and $\langle \sigma_{\text{eff}} v \rangle$ is the effective annihilation cross section. We defined the $'$ notation as $' \equiv \left( 1 - \frac{1}{4} \frac{d \ln g_*(x)}{dx} \right)^{-1} \frac{1}{dx}$ with the effective relativistic degrees of freedom $g_*(x)$ which is constant in the adiabatic expansion universe. If we consider only the decay part of the Boltzmann equation after freeze-out, DM particles are approximately decreasing with the rate $1 - \exp \left( -\Gamma/2H(x) \right)$ in number. Otherwise, they are decreasing with the rate $s \langle \sigma_{\text{eff}} v \rangle / H$ in number for annihilation. The decreasing rate by annihilation $\langle \sigma_{\text{eff}} v \rangle \sim 10^{-26}$ cm$^3$ sec$^{-1}$ is much larger than the one by decay $\Gamma \sim 10^{-26}$ sec$^{-1}$. For example, the decreasing rate will be $10^{-11}$ by decay and $10^{-6}$ by annihilation in the present day universe $H_0 \sim 10^{-16}$ sec$^{-1}$, $s_0 \sim 3000$ cm$^{-3}$. The difference must be much larger at freeze-out. The annihilation dominantly contributes to the time evolution of the DM number density. We thus neglect the contribution of DM decay to the time evolution Boltzmann equation. These
small decreasings must be negligible to other astrophysical and cosmological observations as well.

The triplet DM has three components \( \{ \psi^+, \psi^0, \psi^- \} \), and each component must have the similar thermal history and be nearly degenerate. We need include coannihilation effects in the calculation of the relic density. The coannihilation effects can be described in the effective cross section [34] with the following form

\[
\sigma_{\text{eff}} = \sum_{i,j} \frac{\sigma_{ij} g_i g_j}{g_{\text{eff}}^2} (1 + \Delta_i)^{3/2} (1 + \Delta_j)^{3/2} e^{-x(\Delta_i + \Delta_j)},
\]

where \( \Delta_i = (M_i - M) / M \) (\( i = +, 0, - \) and \( M = M_0 \)), \( g_{\text{eff}} = \sum g_i (1 + \Delta_i)^{3/2} \exp (-x\Delta_i) \) with \( g_i \) internal degrees of freedom of DM components and \( \sigma_{ij} \) is the cross section between \( i \) and \( j \). Four processes are related to the calculation of the effective cross section, \( \psi^0 \psi^0, \psi^+ \psi^-, \psi^\pm \psi^0, \psi^\pm \psi^\pm \) annihilations. The mass difference between our DM components are 160 – 170 MeV [35]. For such small mass difference, \( \Delta_{i,j} \) are negligible. The effective cross section \( \sigma_{\text{eff}} \) becomes the average of all relevant cross sections in this case, and we get the effective annihilation cross section \( \langle \sigma_{\text{eff}} v \rangle \simeq 3\pi \alpha_g^2 / M^2 \) where \( \alpha_g = g^2 / 4\pi \) is the weak fine structure constant. From the Boltzmann equation (3) with the relation \( Y = Y_+ + Y_0 + Y_- \), the DM relic density \( (\Omega_{\text{DM}} h^2 \simeq 0.12) \) can be, according to the study of wino DM in [36] and minimal DM in [37] for annihilations through the operator \( \overline{\psi} \mathcal{M} \psi \), explained with DM mass around 2.7 TeV.

IV. DARK MATTER DECAY AND COSMIC RAY SIGNALS

The DM decay and annihilation into SM particles in the universe would contribute to the observed cosmic rays. The decay rate \( (\Gamma \sim 10^{-26} \text{sec}^{-1}) \) is larger than the annihilation rate \( (n_{\text{DM}} \langle \sigma v \rangle \sim 10^{-31} \text{sec}^{-1}) \) at present. The contribution of DM decay to the cosmic rays are considered. The DM can decay into three body final states through the lepton number violating interaction, and we get interested in the decay mode \( \psi \rightarrow e^+_i e^-_j \nu_j \) \( (\bar{e}_i^- e^+_j \overline{\nu}_j) \) where \( i, j \) are flavor indices as depicted in Fig. 1. The decay rate results in

\[
\Gamma = \sum_{i,j} \frac{1}{64\pi^3 M} \int_0^{\frac{1}{2} M} dE_1 \int_{\frac{1}{2} M - E_1}^{\frac{1}{2} M} dE_2 \langle |\mathcal{M}|^2 \rangle = \sum_{i,j} \frac{g_i^2 g_j^2}{6144\pi^3} \frac{M^5}{M_\chi^4},
\]
where $\mathcal{M}$ is the scattering amplitude for this decay process and the angle bracket means averaging over initial spins and summing over final spins. All the final states are assumed to be massless. Notice that the maximum energy which a produced particle can have is $M/2$. The DM lifetime is

$$\tau_{\text{DM}} = \frac{1}{\Gamma} \simeq 10^{26}\text{ sec} \left( \frac{2700\text{ GeV}}{M} \right)^5 \left( \frac{M_{\chi}}{10^{15}\text{ GeV}} \right)^4 \frac{(0.3)^2(0.3)^2}{\sum_{i,j}(y_{\psi i}^2)(y_{\ell j}^2)^2}. \quad (6)$$

As far as Yukawa couplings are not seriously fine-tuned, the lifetime is of the order of $10^{26}\text{ sec}$ for Higgs triplet mass around $10^{15}\text{ GeV}$.

Recently, the cosmic ray anomalies more clearly appeared in the positron spectrum. The AMS-02 \[38\] has observed a steep rise of the positron fraction over the theoretical expectation up to 350 GeV in kinetic energy, and the PAMELA \[39\] made new measurements with a steep rise that extend the previous measurements \[40\] up to 300 GeV. The AMS-02 data show much higher precision and wider energy extension. Their results must be consistent in their systematic errors, however the spectrum of AMS-02 tends to be softer. Both results must require additional sources of their origin in the galaxy. An excess over the theoretical prediction also appeared in electrons-plus-positrons measurements at the Fermi LAT \[41\] up to $\sim 1–2$ TeV in kinetic energy, combined with HESS results \[42, 43\].

In Fig. 2, we show the predicted positron fraction and the electrons-plus-positrons flux by DM decay with mass 2.5 TeV. The predictions are made for the democratic decay with a universal coupling $(l^+l^−\nu)$, muon dominant decay $(\mu^+\mu^−\nu)$ and tauon dominant decay $(\tau^+\tau^−\nu)$. The primary electron flux of the astrophysical background is from PAMELA electron flux fit \[44\] with the spectral index $−3.18$ (injection index: $−2.66$) above the energy region influenced by the solar wind ($\geq 30\text{ GeV}$). The secondary positron flux of the background is from the GALPROP conventional model \[45\] in the analytic form \[46\]. The density profile of
FIG. 2: Predicted cosmic ray signals in $l^+l^-\nu, \mu^+\mu^-\nu, \tau^+\tau^-\nu$ decay channels with DM mass 2.5 TeV. Left panels: Positron fraction with experimental data, AMS-02 [38], PAMELA [39, 40], Fermi LAT [50]. Right panels: Positrons-plus-electrons flux with experimental data, PAMELA (electron only) [44], Fermi LAT [41], HESS [42, 43], PPB-BETS [51], and ATIC [52]. The bold dotted line shows the astrophysical background. Solar modulation is taken into account by using the force field approximation with the Fisk potential 600 MV.
FIG. 3: Same as Fig. 2, but dark matter decay with branching ratios, $B_e = 6\%, B_\mu = 6\%$ and $B_\tau = 88\%$, and life time $2.0 \times 10^{26}$ sec.

the Milky Way halo is adopted to be the Navarro-Frenk-White (NFW) distribution \[47\] and the MED propagation model \[48\] is selected for galactic cosmic ray transport. The similar plots exist in Ref. \[46\] with various DM masses, and Ref. \[49\] for tauon dominant decay $(\tau^+\tau^-\nu)$ with DM mass of 3 TeV. The predictions must be very similar. Our predictions of $l^+l^-\nu$ with lifetime $5.6 \times 10^{26}$ sec and $\mu^+\mu^-\nu$ with lifetime $1.7 \times 10^{26}$ sec are likely to fit both PAMELA results of the positron excess and Fermi LAT measurements of electrons-plus-positrons flux simultaneously, but they are in tension with AMS-02 energy spectrum above 100 GeV. Otherwise, the prediction of $\tau^+\tau^-\nu$ with lifetime $1.2 \times 10^{26}$ sec is likely to fit the AMS-02 result, but it cannot explain the Fermi LAT measurements. It has already been noticed a difficulty on fitting the AMS-02 and Fermi LAT results together, and there are studies on how to relax the tension \[53\].

In this work we calibrate predictions by providing different branching ratios in each channel. In most studies, a simple or single channel has been adopted to fit AMS-02 and Fermi LAT results simultaneously such that we did in Fig. 2. Our prediction in $l^+l^-\nu$ and $\mu^+\mu^-\nu$ channels is much harder than the AMS-02 result above 100 GeV, otherwise the prediction in the $\tau^+\tau^-\nu$ channel is softer. In electrons-plus-positrons spectrum, our
prediction in the $l^+l^-\nu$ channel shows a sharp feature near the maximum energy, otherwise the prediction in the $\tau^+\tau^-\nu$ channel is very soft near the energy. If our DM can decay into each lepton with different branching ratios, it is possible that we make an appropriate fit of AMS-02 and Fermi LAT measurements together. We show an appropriate fit in Fig. 3 with branching ratios, $B_e = 6\%$, $B_\mu = 6\%$ and $B_\tau = 88\%$ and the lifetime $2.0 \times 10^{26}$ sec. The predictions with different branching ratios are likely to fit AMS-02 and Fermi LAT measurements together. Other divisions of the branching ratio might provide better fits\(^3\).

V. CONCLUSIONS

We proposed a triplet dark matter model based on the standard two Higgs doublet model and seesaw mechanism with Higgs triplets. The lepton asymmetry arises through the operators relevant to the neutrino mass ($\Delta L = 2$) and dark matter decay ($\Delta L = 1$). Our dark matter candidate can annihilate and decay into SM particles. The time evolution of the dark matter number is governed by (co)annihilations in the expanding universe, and its mass is constrained by the observed relic density. The dark matter is no longer stable, and can slowly decay into three body final states (two charged leptons and one neutrino). The decay products would contribute to the observed cosmic rays, and they are able to explain cosmic ray anomalies in the positron spectrum observed at AMS-02, PAMELA and Fermi LAT. A noticeable point is that if dark matter particles decay into each lepton with different branching ratios, cosmic ray anomalies in AMS-02 results of the positron fraction and the Fermi LAT measurements of the electrons-plus-positrons flux could be simultaneously accounted for from its decay products.

\(^3\) Flavor mixing channels such as $e^+\mu^-\nu_\mu$, $\mu^+\tau^-\nu_\tau$ and $\tau^+e^-\nu_e$ are also possible in our model. Predictions in each flavor mixing channel are, according to Ref. [54], unlikely to fit AMS-02 and Fermi LAT measurements together. We might consider a calibration with the flavor mixing channels. However, the spectra are dominantly determined by the spallation of incident particles in the order $e^- (e^+), \mu^- (\mu^+)$ and $\tau^- (\tau^+)$, and so there would be no big difference from predictions in flavor conserving channels. For example, the spectra in $\mu^+\mu^-\nu_\mu$ and $\mu^+\tau^-\nu_\tau$ channels are determined by the spallation of $\mu^+$. The flavor mixing channels are just involved in the detailed spectral shape.
FIG. 4: The decay of $\chi_1^* \rightarrow \ell\ell, \psi e$ at tree level and in one-loop order. A lepton asymmetry is generated by their interference.

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Appendix: Leptogenesis

A lepton asymmetry can be generated in the decay of Higgs triplet $\chi$ if the number of Higgs triplets is two or more. We re-express the Lagrangian of Eq. (1) in the form

$$y_{\psi k} \text{Tr}(\psi^\dagger \chi_k) e^\ell + y_{\ell k} \ell i \sigma_2 \chi_k e + \mu_{1k} \phi_1 \chi_k i \sigma_2 \phi_1 + \mu_{2k} \phi_2 \chi_k i \sigma_2 \phi_2 + \text{h.c.}, \quad (A.1)$$

where $k = 1, 2$ is a species index of $\chi$. If there is only one $\chi$, the relative phase among couplings $y_{\psi k}, y_{\ell k}, \mu_{1k}$ and $\mu_{2k}$ can be chosen real. There would be no CP-violating interaction. With two $\chi$'s, two relative phases must remain among the couplings. A lepton asymmetry is dynamically generated by the interference between the tree and one-loop level decay amplitudes, as shown in Fig. 4. There is no one loop vertex correction. In general, the mass of $\chi$'s is different. The heavy particle $\chi_2$ would decay at higher temperature (earlier time), and the lepton asymmetry by decay of $\chi_2$ will be washed out by the lepton number violating interaction of the light particle $\chi_1$. Hence we only consider the lepton asymmetry by decay of the light one $\chi_1$.

The lepton asymmetry per decay (net lepton number) is defined by the difference between the decay of $\chi_1, \chi_1^*$ particles,
\[ \delta_l = 2 \left[ B(\chi_1^* \rightarrow ll) - B(\chi_1 \rightarrow l' l') \right], \]  
\[ \delta_\psi = B(\chi_1^* \rightarrow l\psi) - B(\chi_1 \rightarrow l' \psi). \]  
(A.2)  
(A.3)

Since our DM couples to charged leptons with \( \Delta L = 1 \), we have an additional contribution. The \( \delta_l \) is different from \( \delta_\psi \) by the factor 2, because two leptons are produced per decay. The total lepton asymmetry will be \( \delta_L = \delta_l + \delta_\psi \).

If we employ the procedure of Ref. [6] for detailed calculations of the lepton asymmetry, the lepton asymmetry per decay results in

\[
\delta_l = \frac{1}{8\pi^2} \Im \left[ \frac{(\mu_{11} \mu_{12} + \mu_{21} \mu_{22} + M_1 M_2 y_{\psi 1} y_{\psi 2}) y_{\ell 1} y_{\ell 2}}{M_2^2 - M_1^2} \right] \left[ \frac{M_1}{\Gamma_1} \right],
\]

\[
\delta_\psi = \frac{1}{16\pi^2} \Im \left[ \frac{(\mu_{11} \mu_{12} + \mu_{21} \mu_{22} + M_1 M_2 y_{\psi 1} y_{\psi 2}) y_{\psi 1} y_{\psi 2}}{M_2^2 - M_1^2} \right] \left[ \frac{M_1}{\Gamma_1} \right],
\]

where \( M_{1,2} \) are masses of \( \chi_{1,2} \). All the final states are assumed to be massless. The notations we used are \( y_{\ell 1} y_{\ell 2} = \sum_{i,j=e,\mu,\tau} y_{\ell 1 i} y_{\ell 2 j} \) and \( y_{\psi 1} y_{\psi 2} = \sum_{i=e,\mu,\tau} y_{\psi 1 i} y_{\psi 2 i} \). The triplet decay width at tree level is

\[
\Gamma_1 = \frac{M_1}{8\pi^2} \left( y_{\ell 1} y_{\ell 2}^* + y_{\psi 1} y_{\psi 2}^* + \frac{\mu_{11}^2 + \mu_{22}^2}{M_1^2} \right)
\]

(A.4)  
(A.5)

in the notations, \( y_{\ell 1} y_{\ell 2}^* = \sum_{i,j=e,\mu,\tau} y_{\ell 1 i} y_{\ell 2 j}^* \) and \( y_{\psi 1} y_{\psi 2}^* = \sum_{i=e,\mu,\tau} y_{\psi 1 i} y_{\psi 2 i}^* \). The produced lepton asymmetry will be \( Y_L = n_L/s \sim \delta_L/g_* \) with the entropy density \( s \sim g_* n_\gamma \). At a temperature above electroweak phase transition, a part of the lepton asymmetry gets converted to the baryon asymmetry via the \( SU(2)_L \) sphaleron processes and

\[ Y_B = S_B Y_L \sim S_B \delta_L/g_* \].

With \( g_* \sim 100 \) and \( S_B \sim 0.5 \), the baryon asymmetry \( Y_B \sim 10^{-10} \) could be accounted for by \( \delta_L \sim 10^{-8} - 10^{-7} \). This small value of \( \delta_L \) is easily acquired from Eqs. (A.4,5). Although the mass of these triplets is around \( 10^{15} \) GeV, there is still
a possibility that the decay is faster than the expansion rate of the universe. In this case, the lepton asymmetry will be approximately suppressed by factor $1/K (\ln K)^{0.6}$ where $K = \Gamma_1 / H$. Near $K = 1$, this suppression would be easily restored by a slight enhancement of $\delta_L$. Otherwise, the detailed time evolution Boltzmann equations are required in order to predict the exact lepton asymmetry for $K \ll 1$.

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