Triplet dark matter from leptogenesis

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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 a 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.

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Recent progress in cosmology and particle physics has eluded scientists for more exact science. The Planck experiment 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 Friedmann-Robertson-Walker 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 [1] 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 [2] 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 [3] 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[1] [4]. 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[2] ψ with a $SU(2)_L$ weak charge is considered as a DM candidate with a lifetime around 10^{26} sec. The seesaw mechanism with a heavy triplet scalar (Higgs triplet) χ is employed to generate the neutrino mass [5] and the lepton asymmetry [6] by lepton number violating interaction at the mass scale of χ. We consider the standard two-Higgs-doublet model (2HDM) as a low energy effective theory.

If our DM candidate is Z_2 odd, the DM candidate ψ is completely stable in the SM. The only interaction is an annihilation into SM particles through the operator $\bar{\psi}\not{W}\psi$. However, if we mind the seesaw mechanism with at least a heavy Higgs triplet χ 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 with Z_2 symmetry [7]; that is, d^c, e^c, and one Higgs doublet ϕ_1 are Z_2 odd, and u^c and the other Higgs doublet ϕ_2 are Z_2 even. Our Z_2-odd DM candidate ψ is thus allowed to couple to Z_2-odd charged leptons with the Higgs triplet χ. It can thus decay into three-body final states by a χ exchange. The relevant potential which can describe interactions with new particles is given by

$$ig\bar{\psi}\not{W}\psi + y_\psi \mathrm{Tr}(\psi\chi^\dagger)e^c + y_\ell \ell i\sigma_2\chi\ell + \mu_1\phi_1\chi i\sigma_2\phi_1 + \mu_2\phi_2\chi i\sigma_2\phi_2 + \mathrm{H.c.}, \quad (1)$$

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[1]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 a Higgs mass with 126 GeV. Hence electroweak baryogenesis is practically ruled out.

[2]The ψ has three components $\{\psi^+, \psi^0, \psi^-\}$, and the neutral component is our DM candidate. Since other components are in the same set, the ψ is called the triplet DM. In this paper, the symbol ψ is also referred to as the DM unless otherwise noted.

where flavor indices are suppressed. The symbol ℓ stands for the left-handed lepton doublet, and the components of Higgs doublets are $\{\phi^-_{1,2}, \phi^0_{1,2}\}$ 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:

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

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:

$$m_\nu \simeq y_\ell \frac{(\mu_1 v_1^2 + \mu_2 v_2^2)}{2M_\chi^2}, \tag{2}$$

where M_χ is the mass of the Higgs triplet and $v_1/\sqrt{2}$ ($v_2/\sqrt{2}$) is the vacuum expectation value of ϕ_1 (ϕ_2). This form is reduced to the usual standard form with $v^2 = v_1^2 + v_2^2 \simeq 246$ 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 [2] from the analysis of cosmological data such as the cosmic microwave background radiation and baryon acoustic oscillations. On the other hand, there exists at least one neutrino mass eigenstate with a mass of at least 0.04 eV [8] from atmospheric neutrino oscillations. The mass scale of χ is of the order of 10^{10}–10^{16} GeV, depending on the couplings y_ℓ, μ_1, and μ_2. The lepton asymmetry may arise in the lepton number violating operators relevant to the neutrino mass ($\Delta L = 2$) and DM decay ($\Delta L = 1$) if the number of Higgs triplet is two or more. A lepton asymmetry is dynamically generated by the interference between the tree and one-loop level decay amplitudes, as shown in Fig. 1. There is no one-loop vertex correction. Since our DM couples to charged leptons with Higgs triplets, we have an additional contribution. Successful leptogenesis may be acquired for the Higgs triplet mass of the order of 10^{15} GeV. However, the leptogenesis to explain the observed BAU is possible for the Higgs triplet mass less than 10^{15} GeV if the CP violation in the χ decay is large enough to compensate for the wash-out effect [6].

In our model, the DM can decay and annihilate. The time evolution Boltzmann equation of DM number density is given by

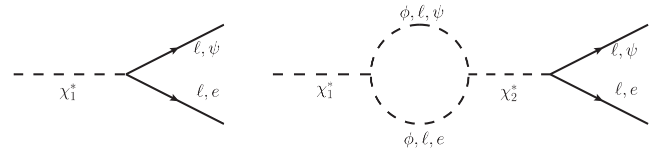

FIG. 1. The decay of $\chi_1^* \longrightarrow \ell\ell, \psi e$ at tree level and in one-loop order. A lepton asymmetry is generated by their interference.

$$Y'(x) = -\frac{\Gamma}{xH}(Y - Y_{\rm eq}) - \frac{s\langle\sigma_{\rm eff} v\rangle}{xH}(Y^2 - Y_{\rm eq}^2), \tag{3}$$

where $x = M/T$ is the inverse temperature with DM mass M, Y ($Y_{\rm eq}$) is the (equilibrium) number density in units of entropy density s, H is the Hubble parameter, Γ is the DM decay rate (width), and $\langle\sigma_{\rm eff} v\rangle$ is the effective annihilation cross section. We defined the $'$ notation as $' \equiv (1 - \frac{x}{4}\frac{d \ln g_*(x)}{dx})^{-1} \frac{d}{dx}$ 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 $1 - \exp(-\Gamma/2H(x))$ in number. Otherwise, they are decreasing with the rate $s\langle\sigma_{\rm eff} v\rangle/H$ in number for annihilation. The decreasing rate by annihilation $\langle\sigma_{\rm eff} v\rangle \sim 10^{-26}$ 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. This small decrease 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 a similar thermal history and be nearly degenerate. The mass difference between our DM components is 160–170 MeV [9]. We need to include coannihilation effects in the calculation of the relic density. Four processes are related to the calculation of the effective cross section: $\psi^0\psi^0$, $\psi^+\psi^-$, $\psi^\pm\psi^0$, and $\psi^\pm\psi^\pm$ annihilations. The coannihilation effects can be described in the effective cross section $\sigma_{\rm eff}$ [10], which becomes the average of all relevant cross sections in this case, and we get the effective annihilation cross section $\langle\sigma_{\rm eff} v\rangle \simeq 3\pi\alpha_g^2/M^2$, 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 ($\Omega_{\rm DM}h^2 \simeq 0.12$) can be, according to the study of wino DM in [11] and minimal DM in [12] for annihilations through the operator $\bar{\psi}\not{W}\psi$, explained with a DM mass around 2.7 TeV.

The DM decay and annihilation into SM particles in the Universe would contribute to the observed cosmic rays. The decay rate ($\Gamma \sim 10^{-26}$ sec^{-1}) is larger than the annihilation rate ($n_{\rm DM}\langle\sigma v\rangle \sim 10^{-31}$ sec^{-1}) at present.

The contribution of DM decay to the cosmic rays is considered. The DM can decay into three-body final states through the lepton number violating interaction, and we get interested in the decay mode $\psi \longrightarrow e_i^+ e_j^- \nu_j (e_i^- e_j^+ \bar{\nu}_j)$, where i, j are flavor indices. The decay rate results in

$$\Gamma = \sum_{i,j} \frac{1}{64\pi^3 M} \int_0^{\frac{1}{2}M} dE_1 \int_{\frac{1}{2}M - E_1}^{\frac{1}{2}M} dE_2 \langle |\mathcal{M}|^2 \rangle = \sum_{i,j} \frac{y_{\psi_i}^2 y_{\ell j}^2}{6144\pi^3} \frac{M^5}{M_\chi^4}, \quad (4)$$

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

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

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

Recently, the cosmic ray anomalies more clearly appeared in the positron spectrum. The AMS-02 Collaboration [13] has observed a steep rise of the positron fraction over the theoretical expectation up to 350 GeV in kinetic energy, and the PAMELA Collaboration [14] made new measurements with a steep rise that extend the previous measurements [15] 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 [16] up to ∼1–2 TeV in kinetic energy, combined with HESS results [17,18]. There are several models to accommodate the decaying dark matter to account for the cosmic ray anomalies, dark matter in grand unification models [19–24], sterile neutrino dark matter [25,26], gravitino dark matter [27–39], Goldstino dark matter [40,41], and instanton-mediated dark matter [42]. Their results are likely to fit the PAMELA and Fermi LAT results. However, a difficulty has been noticed on fitting the AMS-02 and Fermi LAT results together, and there are studies on how to relax the tension [43].

In most studies, a simple or single channel has been adopted to fit AMS-02 and Fermi LAT results simultaneously. In this work, we calibrate predictions by providing different branching ratios in each channel. We show an appropriate fit in Fig. 2 with mass 2.5 TeV for branching ratios $B_e = 6\%$, $B_\mu = 6\%$, and $B_\tau = 88\%$ and the lifetime 2.0×10^{26} sec. The primary electron flux of the astrophysical background is from the PAMELA electron flux fit [44]

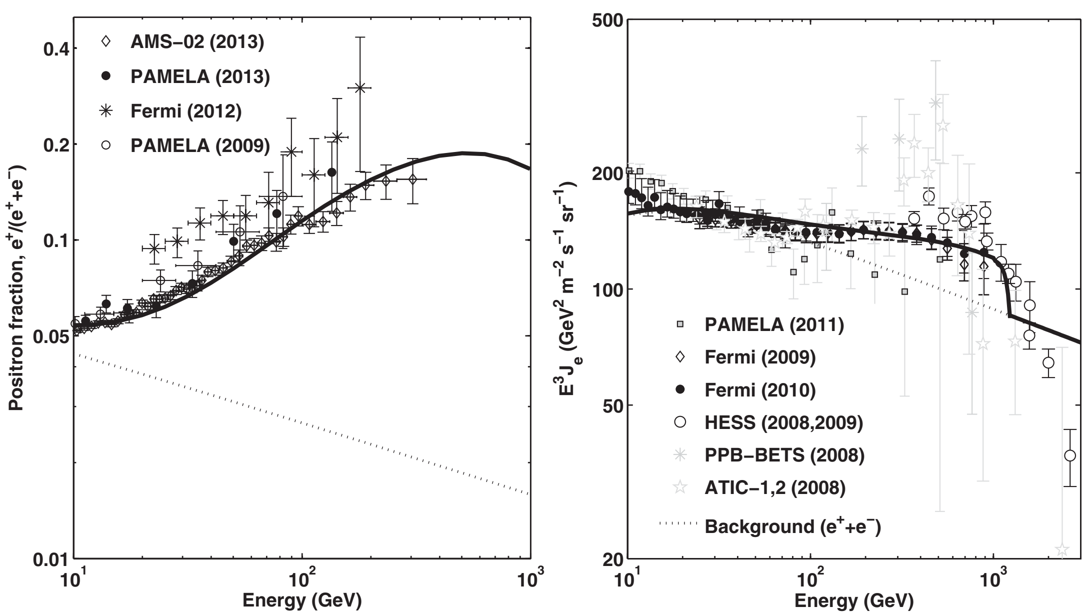

FIG. 2. Predicted cosmic ray signals with DM mass 2.5 TeV for branching ratios $B_e = 6\%$, $B_\mu = 6\%$, and $B_\tau = 88\%$ and lifetime 2.0×10^{26} sec. Left panels: Positron fraction with experimental data: AMS-02 [13], PAMELA [14,15], and Fermi LAT [49]. Right panels: Positrons-plus-electrons flux with experimental data: PAMELA (electron only) [44], Fermi LAT [16], HESS [17,18], PPB-BETS [50], and ATIC [51]. 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.

with the spectral index −3.18 (injection index −2.66) above the energy region influenced by the solar wind (≥30 GeV). The secondary positron flux of the background is from the Galactic Propagation conventional model [45] in the analytic form [46]. The density profile of the Milky Way halo is adopted to be the Navarro-Frenk-White distribution [47], and the median propagation model [48] is selected for galactic cosmic ray transport. 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]

In conclusion, 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 comic 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.

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[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. [52], 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 μ^+. The flavor-mixing channels are just involved in the detailed spectral shape.

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