Baryogenesis and Dark Matter in U(1) Extensions

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A brief review is given of some recent works where baryogenesis and dark matter have a common origin within the U(1) extensions of the standard model and of the minimal supersymmetric standard model. The models considered generate the desired baryon asymmetry and the dark matter to baryon ratio. In one model all of the fundamental interactions do not violate lepton number, and the total $B-L$ in the Universe vanishes. In addition, one may also generate a normal hierarchy of neutrino masses and mixings in conformity with the current data. Specifically one can accommodate $\theta_{13} \sim 9^\circ$ consistent with the data from Daya Bay reactor neutrino experiment.

Keywords: Baryogenesis, Dark Matter, Neutrino, Daya Bay

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 that the amount of dark matter and visible matter are comparable. The fact that dark matter and visible matter are comparable in size points to the possibility of a common origin of the two. Here we discuss classes of models where baryon asymmetry and dark matter have a common origin within the framework of U(1) extensions of the standard model (SM) and of the minimal supersymmetric standard model (MSSM).

The basic tenets of generating matter over anti-matter are well-known and consist of three conditions:

1. the existence of baryon (or lepton) number violation, the presence of C and CP violating interactions, and out of equilibrium processes. One suggestion for explaining the comparable size of dark matter and visible matter is the so-called asymmetric dark matter hypothesis where the dark particles are in thermal equilibrium with the SM (MSSM) particles in the early universe, and thus their chemical potentials are of the same order. The satisfaction of dark matter and visible matter ratio $\Omega_{DM}/\Omega_B \approx 5.5$ can then be achieved via a constraint on the dark matter mass (for reviews see[2]). More specifically, the asymmetry can transfer from the visible sector to the dark sector via the asymmetry transfer interaction $L_{asy} = \frac{1}{M_{asy}} O_{DM} O_{asy}$, where $M_{asy}$ is the scale of the interaction, $O_{asy}$ is an operator constructed from SM (MSSM) fields which carries a non-vanishing $B-L$ quantum number while $O_{DM}$ carries the opposite $B-L$ quantum number. This interaction would decouple at some temperature greater than the dark mat-
As the Universe cools down, the dark matter asymmetry freezes at the order of the baryon asymmetry, which explains the observed relation between the amount of baryon and dark matter. In we discussed asymmetric dark matter in the \(U(1)_{L_\mu - L_\tau}\) and \(U(1)_{B-L}\) Stueckelberg extensions of the SM and of MSSM.

In what follows we discuss two model classes where baryon asymmetry and dark matter have a common origin (for related works see\(^9,10\)). For the first model class, dark matter is generated via the decay of some primordial fields and the asymmetry created by the CP violating decays is then transferred to the visible sector via the asymmetry transfer interaction. In the second model class, leptogenesis takes place with all the fundamental interactions conserving lepton number and leptogenesis consists in generating equal and opposite lepton numbers in the visible and dark sectors. Subsequently the sphaleron processes transmute a part of the lepton asymmetry into baryon asymmetry. In this model class the total \(B - L\) number in the Universe is exactly conserved.

In the model classes referred to above the stability of dark matter is protected by the \(U(1)\) gauge symmetry. A kinetic mixing between the \(U(1)\) and \(U(1)\) gauge bosons allows for dissipation of the symmetric component of dark matter through the exchange of the \(U(1)\) gauge boson. An alternative way of depleting the symmetric component of dark matter is assuming that the \(U(1)\) gauge boson is massless (dark photon). Majorana mass terms for dark particles are forbidden. Consequently, the dark matter asymmetry generated in the early universe would not be washed out by oscillations.

2. Baryogenesis from Dark Sector

We first discuss the model class where primordial fields decay into dark matter and create an asymmetry. The dark matter asymmetry then transmutes into lepton and baryon asymmetries.

2.1. The model

Here we work in a supersymmetric framework. We assume that in the early universe there exist several \(\hat{N}_i\) fields \((i \geq 2)\) with masses \(M_i\), where \(\hat{N} = (N, \tilde{N})\) and \(N\) is the Majorana field and \(\tilde{N}\) is the super-partner field. The scalar field of the lightest \(\hat{N}_i\) superfields could play the role of the inflaton, and \(\hat{N}_i\) can also be right-handed neutrinos as suggested in earlier works. The dark sector is comprised of \((\hat{X}, \hat{X}^c, \hat{X'}, \hat{X'}^c)\) which are charged under the gauge group \(U(1)_x\) with charges \((+1, -1, -1, +1)\) while the MSSM fields are not charged under \(U(1)_x\). We assume the \(\hat{N}_i\) carry a non-vanishing lepton number \(+2\), \(\hat{X}, \hat{X'}\) carry lepton number \(-1\) and

\(^a\) In the non-supersymmetric case, the simplest model with interaction \(\mathcal{L} \sim \lambda_i N_i \hat{X}^c X' + h.c.\), where \(\lambda_i\) are complex coupling constants, \(N_i\) are complex scalars and \(i \geq 2\), \(X, X'\) are Dirac fermions, does not work. Namely, the decay of \(N_i\) as well as \(N_i^*\) does not generate an asymmetry between \(X, X'\) and \(\hat{X}, \hat{X'}\).
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Fig. 1. Loop diagrams responsible for the genesis of dark matter asymmetry from the decay of $N_i$ to final states $XX'$ and there are similar diagrams for the decay of the $N_i$ to the final states $\tilde{X}X'$, and for the decay of $\tilde{N}_i$ to $XX'$ and to $\tilde{X}\tilde{X}'$.

$\hat{X}^c, \hat{X}'^c$ carry lepton number $+1$. The superpotential of the model is given by

$$W = \lambda_i \hat{N}_i \hat{X} \hat{X}' + \frac{1}{M_{\text{asy}}^2} \hat{X} \hat{X}' (LH_u)^2 + m \hat{X} \hat{X}^c + m' \hat{X}' \hat{X}'^c,$$

where the couplings $\lambda_i$ are assumed to be complex. $W$ is invariant under both $U(1)_x$ and lepton number, and the first term is responsible for generating an asymmetry in the dark sector whereas the second term is responsible for transferring the asymmetry generated in the dark sector to the visible sector. Finally we add mass terms for $\hat{N}_i$ to the superpotential, i.e., a term $W \sim \frac{1}{2} M_i \hat{N}_i \hat{N}_i$, which violates lepton number.

We assume the mass hierarchy $M_i \gg m + m'$ so that in the early universe, and the out-of-equilibrium decays of $\hat{N}_i$ generates dark matter through $N_i \rightarrow X \hat{X}'$, $\hat{X}X'$, $\hat{X}X'^*$, $\hat{X}'X^*$ and $\tilde{N}_i \rightarrow XX'$, $\tilde{X}\tilde{X}'$. Further, the CP violation due to the complex couplings $\lambda_i$ generates an excess of $X, X'$ over their anti-particles $\tilde{X}, \tilde{X}'$ carrying the opposite lepton numbers. Thus the decays of $\hat{N}_i$ produce a lepton number asymmetry in the dark sector. The lepton asymmetry generated in this fashion in the dark sector is then transferred to the visible sector through the asymmetry transfer interaction, and thus leptogenesis occurs. Finally, a part of lepton number asymmetry of the visible sector then transmutes to baryon number asymmetry via the sphaleron interactions. In the simplest model we have $i = 2$, and we assume $\tilde{N}_2$ mass $M_2$ is much larger than $\hat{N}_1$ mass $M_1$.

The dark matter asymmetry arises from the interference of the one-loop diagrams shown in Fig. 1 with the tree-level diagrams, similar to the conventional leptogenesis diagrams. The asymmetries, i.e., the excess of $\hat{X}, \hat{X}'$ over their anti-particles $\tilde{X}, \tilde{X}'$ are measured by $\epsilon_{X\hat{X}'}, \epsilon_{\hat{X}X'}, \epsilon_{XX'}, \epsilon_{\hat{X}'\hat{X}'}$ where the lower indices of $\epsilon$ denote the final state particles. There are two types of loops involved: vertex contribution and wave contribution as shown in Fig. 1. It’s straightforward to compute the above asymmetry parameters $\epsilon_{X\hat{X}'}$ etc. It turns out that the contributions of the vertex diagrams and the wave diagrams satisfy the following relations

$$\epsilon_{X\hat{X}'} = \epsilon_{\hat{X}X'}, \epsilon_{XX'} = \epsilon_{\hat{X}'\hat{X}'}, \epsilon_{XX'} = \epsilon_{\hat{X}'\hat{X}'} = \epsilon_{\text{vertex}},$$

$$\epsilon_{\text{wave}} = \epsilon_{\text{wave}} = \epsilon_{\text{wave}} = \epsilon_{\text{wave}} = \epsilon_{\text{wave}},$$

(2)

(3)
Specifically, we have

\[ \epsilon_{\text{vertex}} = -\frac{1}{8\pi} \frac{\text{Im}(\lambda_1^2\lambda_2^2)}{|\lambda_1|^2} \ln \left( \frac{M_1^2 + M_2^2}{M_2^2} \right), \quad (4) \]

\[ \epsilon_{\text{wave}} = -\frac{1}{8\pi} \frac{\text{Im}(\lambda_1^2\lambda_2^2)}{|\lambda_1|^2} \frac{M_1(M_1 + M_2)}{M_2^2 - M_1^2}. \quad (5) \]

Thus the total asymmetry parameter is the sum of the vertex and the wave contributions and in the limit \( M_2 \gg M_1 \), we obtain

\[ \epsilon = \epsilon_{\text{vertex}} + \epsilon_{\text{wave}} \approx -\frac{1}{4\pi} \frac{\text{Im}(\lambda_1^2\lambda_2^2)}{|\lambda_1|^2} \frac{M_1}{M_2}. \quad (6) \]

The total excess of \( X, \tilde{X}, X', \tilde{X}' \) over \( \tilde{X}, \tilde{X}^*, X', X'^* \) generated by the decay of \( \tilde{N}_1 \) is given by \( \Delta n_X \approx 2\kappa s e / g_s \), where \( s \) is the entropy, \( g_s \approx 228.75 \) is the entropy degrees of freedom for MSSM, and \( \kappa \) is a washout factor due to inverse processes \( X + \tilde{X}', \tilde{X} + X' \to N \) and \( X + X', \tilde{X} + \tilde{X}' \to \tilde{N} \) and in our analysis we set \( \kappa = 0.1 \). The excess of \( \tilde{X}, \tilde{X}' \) then give rise to a non-vanishing \( (B - L)_f \)-number in the early universe: \( (B - L)_f = (+1) \times \Delta n_X \approx 2\kappa s e / g_s \), where \( (B - L)_f \) is the total \( B - L \) in the Universe and \(+1\) indicates each of \( X, X' \) carries a \( B - L \) number +1.

The \( B - L \) asymmetry generated in the visible sector through the asymmetry transfer interaction can be obtained by using the standard thermal equilibrium method introduced in\(^{12}\) For very high temperatures the MSSM fields are ultra-relativistic, hence MSSM fields and dark particles are in thermal equilibrium, which gives rise to relations among their chemical potentials\(^{11,12}\) These relations allow us to express the chemical potentials of all the MSSM fields in terms of the chemical potential of one single field, e.g., \( \mu_L \), the chemical potential of the left-handed lepton doublet. Similarly other quantities of interest, i.e., the total lepton number \( L \), the total baryon number \( B \), and the net \( B - L \) in the visible sector can all be expressed in terms of \( \mu_L \). Specifically we have \( (B - L)_v = -\frac{22}{7} \mu_L \), where \( (B - L)_v \) is the \( B - L \) in the visible sector. Here we assume the asymmetry transfer interaction would decouple above the supersymmetry breaking scale, thus the asymmetry would transfer from the dark sector to the visible sector when all of the MSSM particles are active in the thermal bath. Hence dark particles are in thermal equilibrium with all of the MSSM particles, which gives \( \mu_\tilde{X} + \mu_{\tilde{X}^*} = -\mu_{\tilde{X}^*} - \mu_{\tilde{X}^*} = -\frac{22}{7} \mu_L \). Thus the total dark particle number is given by \( X = \frac{22}{7}(B - L)_v \).

The dark matter mass is determined using the constraint \( \Omega_{DM}/\Omega_B = (X m_{DM})/(B m_B) \approx 5.5 \), where \( m_{DM} \) is the mass of the dark matter particle and \( m_B \) is the baryon mass which is taken to be \( m_B \sim 1 \) GeV. An important subtlety here is that although the total dark particle number is fixed after the asymmetry transfer interaction decouples, the total baryon number changes after this decoupling because of the sphaleron processes. As explained in detail in\(^{13}\) the total baryon number to be used in the computation of \( \Omega_{DM}/\Omega_B \) is \( B_{\text{final}} \) after the sphaleron processes decouple. Thus one has \( m_{DM} = (B_{\text{final}}/X) \cdot 5.5 \) GeV where \( B_{\text{final}} = \frac{30}{97}(B - L)_v \approx 0.31(B - L)_v \)
\(^{13}\) This leads to \( m_{DM} \approx 3.01 \) GeV. The astro-
physical constraint $B_{\text{final}}/s \sim 6 \times 10^{-10}$ can be satisfied with $\epsilon \sim 4 \times 10^{-6}$, which sets bounds for the complex couplings $\lambda_i$ and the ratio $M_1/M_2$.

### 2.2. Physics of the dark sector

In order to achieve a viable model one needs to dissipate the symmetric component of dark matter. This can be achieved by gauge kinetic energy mixing of $U(1)_x$ and $U(1)_Y$. The thermally produced dark matter and its anti-matter can annihilate efficiently into SM particles through the $Z'$ boson exchange with a Breit-Wigner enhancement. The kinetic mixing does not generate couplings between the photon and dark sector particles and thus dark matter carries no milli-charge. Consequently there are no experimental constraints from the limits on milli-charges on the parameter $\delta$ which enters in the gauge kinetic energy mixing of $U(1)_x$ and $U(1)_Y$. Thus the strongest experimental constraints on the $Z'$ boson mass and its coupling to the visible sector come from corrections to $g_\mu - 2$ as well as LEP II constraints. These lead to the limit $\delta \lesssim 0.001$. With such constraints, one can deplete the symmetric component of dark matter in sufficient amounts, i.e., less than 10% of the total dark matter relic abundance.

An alternative way of depleting the symmetric component of dark matter is assuming that the $U(1)_x$ gauge boson is massless (dark photon). Then the symmetric component of the dark matter could annihilate into the $U(1)_x$ dark photons and become radiation in the early universe. As shown in, the constraints on the number of extra effective neutrino species $\Delta N_{\text{eff}}$, can be satisfied for a large class of asymmetric dark matter models.

Such dark matter can scatter from quarks within a nucleon through the t-channel exchange of the $Z'$ boson. The spin-independent dark matter-nucleon cross section can be approximately written as $\sigma_{\text{SI}} \sim 4\delta^2 \mu_n^2 g_Y^2 \cos^4 \theta_W m_n^2 / \pi m_{Z'}^2$, where $\mu_n$ is the dark matter-nucleon reduced mass. For our model we find $\sigma_{\text{SI}} \sim 10^{-37} \text{cm}^2$, which is just on the edge of sensitivity of the CRESST I experiment. Thus improved experiment in the future in the low dark matter mass region with better sensitivities should be able to test the model.

As in the supersymmetric case, the $U(1)_x$ gaugino $\chi$ is given a soft mass $L_\chi = m_\chi \tilde{\chi} \chi$. It can then decay into $XX$ or $X'X'$ via the supersymmetric interaction $L \sim \chi XX + \chi X'X' + \text{h.c.}$, where we assume $m_\chi > m_X + m_{\tilde{X}}$. Thus the gaugino $\chi$ decays into dark particles and is removed from the low energy spectrum. One important aspect of the supersymmetric case is that it presents a multi-component picture of dark matter. The total dark matter relic abundance consists of dark sector particles ($\tilde{X}, \tilde{X}^c, \tilde{X}'$, $\tilde{X}'^c$) as well as the conventional lightest supersymmetric particle with R-parity, i.e., the (lightest) neutralino. There exists a significant part of the parameter space of MSSM where the relic density of neutralinos can be 10% or less of the current relic density. The analysis shows that even with 10% of the relic density, the neutralino dark matter would be still accessible in dark matter searches. Thus this feature also offers a direct test of the model in neutralino dark
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matter searches. However, the leptonic dark matter would be difficult to see in direct searches for dark matter as well as in collider experiments because of its small couplings to the visible sector via the $Z'$ boson exchange. Future colliders with higher sensitivity and accuracy may have the possibility to explore the $Z'$ boson with tiny couplings to the SM particles.

3. Cogenesis of Baryon Asymmetry and Dark Matter

We discuss now a model class where leptogenesis takes place with all fundamental interactions not violating lepton number, and the total $B-L$ number in the Universe vanishes. Such leptogenesis leads to equal and opposite lepton numbers in the visible sector and the dark sector. Part of the lepton number generated in the visible sector subsequently transfers to the baryonic sector via sphaleron interactions.

3.1. The model

We begin by considering the set of fields $N_i, \psi, \phi, X, X'$ with lepton number assignments $(0, +1, -1, +1/2, +1/2)$. Here $N_i$ ($i \geq 2$) are Majorana fermions, $\psi, X, X'$ are Dirac fields and $\phi$ is a complex scalar field. The fields $N_i, \psi, \phi$ are heavy and will decay into lighter fields and eventually disappear. 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

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

(7)

where the couplings $\lambda_i$ are assumed to be complex and the couplings $\beta, \gamma$ are assumed to be real. In addition we add mass terms so that

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

(8)

Here $N_i$ have Majorana masses, while $\psi, X, X'$ have Dirac masses. We assume the mass hierarchy $M_i \gg m_1 + m_2, m_1 \sim m_2 \gg m_X + m_{X'}$. Consistent with the above constraint, $m_1, m_2$, the masses of $\psi$ and $\phi$, could span a wide range from TeV scale to scales much higher.

In the early universe, the out-of-equilibrium decays of the heavy Majorana fields $N_i$ produce a heavy Dirac field $\psi$ and a heavy complex scalar field $\phi$. The CP violation due to the complex couplings $\lambda_i$ generates an excess of $\psi, \phi$ over their anti-particles $\bar{\psi}, \bar{\phi}$ which carry the opposite lepton numbers. Since the lepton number carried by $\psi$ and $\phi$ 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, $\psi$ and $\phi$ (as well as their anti-particles) produced in the decay of the Majorana fields $N_i$ will sequentially decay, with $\psi$ (and its anti-particle) decaying into the visible sector fields and $\phi$ (and its anti-particle) decaying into the dark sector fields. Their decays
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Fig. 2. Generation of asymmetry in $\psi, \phi$ over their antiparticles $\bar{\psi}, \phi^*$ from the decay of the Majorana field $N_1$. The lepton number is conserved in these processes.

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 $\bar{\psi} \rightarrow \bar{X} + X'$ and $\phi^* \rightarrow L + H$ 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 $\psi, \phi$ 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.

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 $N_i$ have completely decayed (the decay of $N_i$ does not generate any baryon asymmetry), and thus is equal to the lepton number in the dark sector, i.e., $(B - L)_V = L_d$ where the indices $V, d$ denote the visible sector and the dark sector respectively. We are interested in the relative density of particle species at the time when the sphaleron interactions go out of the thermal equilibrium. After the decoupling of the sphaleron interactions $B$ and $L$ are separately conserved and correspond to the $B$ and $L$ seen today. Recall the final (currently observed) value of the baryon number density $B_{\text{final}} \approx 0.31(B - L)_V$ assuming that $X$ and $X'$ have the same mass, we obtain $m_X = m_{X'} \approx 0.85$ GeV.

We turn now to the detail of the generation of the asymmetry between $\psi, \phi$ and $\bar{\psi}, \phi^*$. We assume there are two Majorana fields $N_1$ and $N_2$ with $N_2$ mass $M_2$ being much larger than the $N_1$ mass $M_1$, i.e., $M_2 \gg M_1$. The diagrams that contribute to it are shown in Fig. 2 where the Majorana particles $N_i$ decay into the Dirac fermion $\psi$ and the complex scalar $\phi$ with $\psi$ and $\phi$ carrying opposite lepton numbers while the Majorana fields $N_i$ carry no lepton number. In this case the asymmetry arising
from the excess of $\psi, \phi$ over $\bar{\psi}, \phi^*$ is given by

$$
\epsilon = \frac{\Gamma(N_1 \to \psi\phi) - \Gamma(N_1 \to \bar{\psi}\phi^*)}{\Gamma(N_1 \to \psi\phi) + \Gamma(N_1 \to \psi\phi^*)} \approx -\frac{1}{8\pi} \frac{\text{Im}(\lambda_1^2\lambda_2^2)}{|\lambda_1|^2 - M_2},
$$

(9)

where we have included both the vertex contribution and the wave contribution. Since the dark sector does not communicate with the visible sector, $(B - L)_\nu$ is equal in magnitude and opposite in sign to the lepton number generated in the visible sector: $(B - L)_\nu = -L_\nu \approx -0.4 s \kappa s / g_*$. where $s$ is the entropy, $\kappa$ is the washout factor and we take $\kappa = 0.1$ and $g_* = 106.75$. Using again $B_{\text{final}} \approx 0.31(B - L)_\nu$, one estimates $|\epsilon| \sim 5 \times 10^{-6}$. The supersymmetric extension of this model is straightforward, as discussed in\textsuperscript{[2]}

### 3.2. Phenomenology of the model

In a manner similar to what was discussed earlier, the symmetric component of dark matter would be sufficiently depleted by annihilating via the $Z'$ gauge boson into SM particles (or annihilating into $U(1)_e$ dark photons), which ensures the asymmetric dark matter to be the dominant component of the current dark matter relic abundance.

An interesting implication of this model class arises in the neutrino sector. Here we add three families of right-handed neutrinos. We assume the coupling $\beta$ is family-dependent, i.e., $\beta \to \beta_i$ where $i = 1, 2, 3$ correspond to $e, \mu, \tau$, c.f., Eq. (7) so the Lagrangian reads

$$
\mathcal{L}' = \beta_i \bar{\psi}_i R L_i \bar{H} + \beta_i' \bar{\psi}_i R L_i H + \mu_i' \bar{\psi}_i R \psi_L + h.c.
$$

(10)

After spontaneous breaking of the electroweak symmetry, the mass terms take the form $\mathcal{L}_m = \bar{\nu}_R^T M \nu_L + h.c.$, where $\bar{\nu}_R = (\bar{\nu}_{R1}, \bar{\nu}_{R2}, \bar{\nu}_{R3})$, and $\bar{\nu}_L = (\nu_{L1}, \nu_{L2}, \nu_{L3})$. For simplicity we assume a symmetrical form for the neutrino mass terms so that

$$
\mathcal{L}'_m = \bar{\nu}_R^T \begin{pmatrix}
0 & 0 & \mu_1 \\
0 & m_{\nu_e} & \mu_2 \\
\mu_1 & \mu_2 & \mu_3
\end{pmatrix} \nu_L + h.c.
$$

(11)

Eq. (11) contains no direct mixings among the neutrino flavor states. However, their mixings with the field $\psi$ automatically leads to neutrino flavor mixings for the mass diagonal states. To exhibit this mixing we diagonalize the matrix of Eq. (11) by an orthogonal transformation. By setting $m_{\nu_e} = 10^{-11}, m_{\nu_\mu} = 1.7 \times 10^{-10}, m_{\nu_\tau} = 2 \times 10^{-9}, m_1 = 2000, \mu_1 = 3.6 \times 10^{-5}, \mu_2 = 8.9 \times 10^{-5}, \mu_3 = 5.9 \times 10^{-4}$ (all masses in GeV) the three neutrino masses in the mass diagonal basis are $m_3 \approx 4.8 \times 10^{-2}$ eV, $m_2 \approx 1.2 \times 10^{-2}$ eV, $m_1 \approx 4.2 \times 10^{-3}$ eV, which is the normal hierarchy of neutrino masses\textsuperscript{[13]} while the mass of the heavy field $\psi$ is still $\sim m_1$. For the neutrino mixings we obtain $\sin^2 \theta_{12} \approx 0.30, \sin^2 \theta_{23} \approx 0.36, \sin^2 \theta_{13} \approx 0.024$, which is in good accord with the experimental determination of the mixing angles. Specifically the model is consistent with the result from the Daya Bay reactor
neutrino experiment of $\theta_{13} \sim 9^\circ$. It is interesting that the model provides an explanation of the neutrino mixings at a fundamental level. The neutrino mixings arise as a consequence of the interaction of the neutrinos with the primordial Dirac field $\psi$ which enters in leptogenesis which points to the cosmological origin of neutrino mixings.

Other implications of the model involve flavor changing processes. For the supersymmetric version of the model, after spontaneous breaking one has interactions of the charged Higgs $H^+$ with charged leptons and $Y$:

$$\mathcal{L}_{H\ell\psi} = \beta_i \bar{Y}_\ell H^+ + h.c.,$$

(12)

where $\ell_i$ denotes the charged leptons and $Y$ is a chiral field with lepton number $-1$. Such interactions will give rise to $\ell_i \to \ell_j \gamma$ processes, where a charged lepton $\ell_i$ converts into a charged lepton $\ell_j$ via exchange of $Y$ while a photon is emitted by the charged Higgs inside the loop, see Fig. 3. Assuming $m_Y^2 \gg m_{H^+}^2$, we obtain the decay rate of the flavor changing process $\ell_i \to \ell_j \gamma$ to be

$$d\Gamma_{\ell_i \to \ell_j \gamma} = \frac{\alpha_{em} (\beta_i \beta_j)^2}{(16\pi)^2} \frac{m_i^3}{M_Y^2},$$

(13)

where $m_i$ is the mass of the decaying charged lepton and we have used $m_i \gg m_j$. The current experimental bounds constrain the couplings to be $\beta_1 \sim \beta_2 \lesssim 3 \times 10^{-3}$ and $\beta_3 \lesssim 2 \times 10^{-4}/\beta_1$ for $M_Y \sim 1$ TeV. One can expect observable effects in these flavor changing processes in future experiments with improved sensitivities.

4. Conclusion

The comparable size of dark matter and visible matter in the Universe points to a possible common origin of the two. Here we discussed two classes of models. In the first model class, the dark matter is generated from the decay of some primordial fields. The asymmetry is generated in the dark sector by the CP violating decays, and then transfer to the visible sector via the asymmetry transfer interaction. In the second model class all of the fundamental interactions conserve lepton number, and leptogenesis occurs when equal and opposite lepton numbers are generated in the visible sector and dark sector. Subsequently the sphaleron processes transmute...
a part of lepton asymmetry to baryon asymmetry. In this model class the total $B - L$ number in the Universe is exactly conserved. Phenomenological aspects of these models were also discussed.

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