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Dirac Leptogenesis in assistance of Dark Matter and Neutrino Mass

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We propose an extension of the standard model with $U(1)_D \times U(1)_{B-L} \times Z_2$ symmetry. With this extension of the model we assumed that the neutrinos are Dirac (*i.e.* $B-L$ is an exact symmetry), and found a simultaneous solution for non zero neutrino masses, Dark Matter(DM) content and the baryon asymmetry of the Universe. The observed baryon assymmetry of the Universe explained through the Dirac leptogenesis with the assistance of DM. The $U(1)_D$ symmetry is broken at a TeV scale and gives mass to a neutral gauge boson Z_D. At one loop level this neutral gauge boson mixes with the standard model Z-boson and paves a path to detect the DM at terrestrial laboratories through spin independent elastic scattering. We explain the neutrino mass through a Lagrangian term, which softly broken by the Z_2 symmetry.

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1. Introduction

Till now there is no evidence found in favour to Majorana nature of neutrinos from neutrinoless double beta decay experiments [1]. So still there is a possibility that the neutrinos might be Dirac in nature. Even though neutrinos are Dirac in nature (i.e. $B-L$ is exactly conserved), the Baryon Asymmetry of the Universe(BAU) can be explained through Dirac leptogenesis [2, 3], which connects the Dirac neutrino mass with the observed BAU. This mechanism works on the point that the equilibration time between left and right-handed neutrinos mediated through SM Higgs (i.e. $Y\overline{\nu_R}H\nu_L$)is much less than $(B+L)$ violating sphaleron transitions above electroweak phase transition. If we can write that $B-L=B-(L_{\rm SM}+L_{\nu_R})=0$[4], then we see that a net $B-L_{\rm SM}$ is generated in terms of L_{ν_R}. The electroweak sphalerons will not act on L_{ν_R}, while the non-zero $B-L_{\rm SM}$ will be converted to a net baryon asymmetry via $B+L$ violating sphaleron transitions.

2. The model and Dirac mass of neutrinos

We extended the SM model with additonal symmetries $U(1)_{B-L}\times U(1)_D\times Z_2$ and the particle content with three right handed neutrinos ν_R which play a role in anomaly cancellation and they are odd under Z_2, with lepton number as 1. We also introduced χ and ψ vector-like fermions which are singlet and doublet under $SU(2)_L$ respectively. They are odd under Z_2 with $U(1)_D$ charge as 1 and the lepton number is same as ν_R . And two heavy scalars $X_{1,2}$, which are odd under Z_2, we introduce here creates equal and opposite asymmetry in both ℓ (left sector) and ν_R (right sector) in the visible sector and also creates an asymmetry in both χ and ψ in dark sector, in their CP-violating out-of-equilibrium decay. The lepton asymmetry stored in the left sector converts to a net baryon asymmetry through $B+L$ violating sphaleron transitions. And the asymmetry which is stored in the right sector remains uneffected until the temperature much below the electroweak phase transion. The asymmetry in ψ converts to χ asymmetry in its out-of-euilibrium decays and we can show that its contribution to the relic abundance is negligible. The lightest particle χ amongst the dark sector paricles acts as DM candidate. In this model the $U(1)_D$ is broken symmetry and gives mass to the gauge boson Z_D, while the $U(1)_{B-L}$ is not a broken symmetry and guarantees the Dirac nature of the neutrinos. The relevant Lagrangian can be written as:

$$\mathscr{L}\supset M_\psi\bar{\psi}\psi+M_\chi\bar{\chi}\chi+\left[f_{kl}\overline{\ell_k}\tilde{X}\nu_{Rl}+\lambda\overline{\psi}\tilde{X}\chi+\text{h.c.}\right]-V(H,X)\,, \tag{2.1}$$

where

$$V(H,X)=-M_H^2H^\dagger H+M_X^2X^\dagger X+\lambda_H(H^\dagger H)^2+\lambda_X(X^\dagger X)^2+\lambda_{HX}(H^\dagger H)(X^\dagger X). \tag{2.2}$$

We allow the Z_2 symmetry to break softly[5] via:

$$\mathscr{L}_{soft}=-\mu^2H^\dagger X+\text{h.c.} \tag{2.3}$$

As a result the Dirac mass of the neutrinos can be generated at tree level. After integrating out the tree level diagram we get the Dirac neutrino mass:

$$M_\nu=\frac{f\langle H\rangle\mu^2}{M_X^2}\,, \tag{2.4}$$

where $\langle H\rangle=174$ GeV, is the Higgs vacuum expectation value. To generate required Dirac masses of the neutrinos of order 0.1 eV, we need the ratio of $\frac{\mu}{M_X}\approx10^{-4}$, assuming here $f\sim10^{-4}$.

3. Lepton asymmetry and dark matter abundance from X-decay

The presence of X-particles and their interactions the mass matrix of X can be replaced with new mass matrix and after diagonalising the new mass matrix we get new mass eigenstates $\xi_1^{\pm}$ and $\xi_2^{\pm}$. For further details [6]. The CP-violation arises via the interference of tree level and one loop self energy correction diagrams and the asymmetry ε_L in the visible sector can be calculated. Using the CP-asymmetry ε_L, we can estimate the generated lepton asymmetry $Y_L \equiv \frac{n_L}{s}$. The abundance of ξ and the amount of lepton asymmetry can be calculated using Boltzmann equations as,

$$\frac{dY_{\xi_1}}{dx} = -\frac{x}{H(M_{\xi_1})} s < \sigma|v|_{(\xi_1\xi_1\to All)} > \left[Y_{\xi_1}^2 - Y_{\xi_1}^{eq2}\right] - \frac{x}{H(M_{\xi_1})}\Gamma_{(\xi_1\to All)}\left[Y_{\xi_1} - Y_{\xi_1}^{eq}\right] \tag{3.1}$$

and

$$\frac{dY_L}{dx} = \varepsilon_L \frac{x}{H(M_{\xi_1})}\Gamma_{(\xi_1\to All)} B_L \left[Y_{\xi_1} - Y_{\xi_1}^{eq}\right], \tag{3.2}$$

where the $x = \frac{M_{\xi_1}}{T}$, is the dimensionless variable. The number density of ξ and the lepton asymmetry are shown in Fig. 1(left panel). Here we have taken coupling constant f as 10^{-4} and the λ as 0.47×10^{-7} and the typical cross-section $\sigma|v|_{\xi_1\xi_1\to All} = 10^{-25}\mathrm{GeV}^{-2}$. The branching ratio is of the $\mathscr{O}(1)$ and $M_{\xi_1} = 10^{10}$ GeV. The sphalerons can transfer a partial lepton asymmetry to a net baryon asymmetry as $Y_B = -0.55 Y_L$. For $\varepsilon_L = 2\times 10^{-7}$ and with the parameters we discussed above gives the baryon asymmetry, $Y_B = -1\times 10^{-10}$.

The relic abundance of χ can come from the CP-conserving and CP-non-conserving decay of heavy scalar ξ, which is nothing but sum of symmetric and asymmetric components of χ, respectively. However we get the contribution of the abundance of the asymmetric component of DM to the correct relic abundance is very small, due to small CP-asymmetry and small branching ratio $B_\chi \equiv Br(\xi_1 \to \psi\chi)$, therefore we neglect it. The symmetric component of χ from the decay of ξ_1 and ξ_2 can be estimated from Boltzmann equations as,

$$\frac{dY_\chi}{dx} = \frac{x}{H(M_{\xi_1})}\Gamma_{(\xi_1\to All)} B_\chi \left[Y_{\xi_1} - Y_{\xi_1}^{eq}\right]. \tag{3.3}$$

where Y_{ξ_1} given in Eq.3.1. The solutions of Eqs. 3.1 and 3.3 are shown in Fig. 1(right panel).

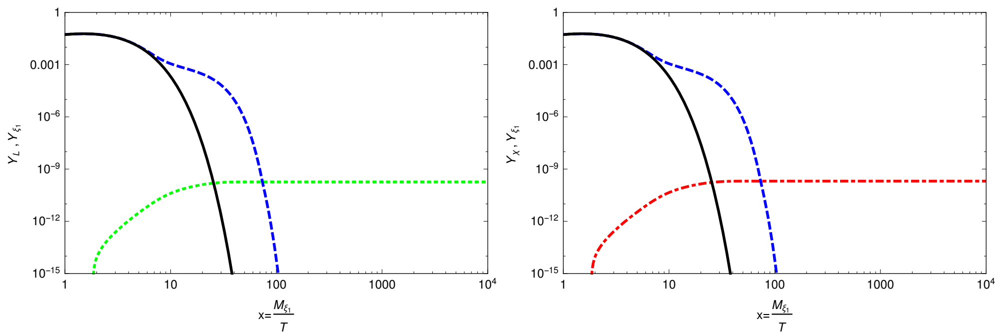

Figure 1: In the left panel the generated lepton asymmetry from the decay of ξ_1. The Green dotted line shows the abundance of lepton asymmetry. In the right panel the Red dotted line shows the abundance of χ DM. The Blue dashed-line shows the abundance of ξ_1 and the Black solid-line shows the equilibrium number density of ξ_1.

Here we have taken the same parameter space as we discussed in the above paragraph and for the DM mass M_χ = 2.5 GeV. To get the observed dark matter abundance($\sim 10^{-10}$), we have used the branching ratio $B_\chi = 2.2 \times 10^{-7}$. This shows that ξ_1 decay significantly to visible sector and rarely to invisible sector to get the correct relic abundance of dark matter and baryon asymmetry.

There are other possibile scattering processes which can populate the χ abundance are $\overline{\psi}\psi \to \overline{\chi}\chi$ mediated by Z_D and $\overline{f}f \to \overline{\chi}\chi$ through mixing of Z and Z_D, in thermal bath apart from ξ-decay. In Fig. 2 we have shown the allowed parameter space, the blue region, in g_D versus M_{Z_D} plane where these processes remain in out-of-equilibrium and hence they remain consistent with relic abundance of DM obtained from ξ decay.

4. Direct detection of χ dark matter

The spin independent elastic scattering cross-section of DM candidate with nuclei can be possible through the $Z - Z_D$ mixing. We get the total cross-section per nucleon to be,

$$\sigma_{SI}^Z \simeq 2.171 \times 10^{-36} cm^2 \tan^2\theta_Z \frac{g_D^2}{(M_{Z_D}/\mathrm{GeV})^2}, \tag{4.1}$$

where we have used DM mass to be 5 GeV. θ_Z is the mixing angle between Z and Z_D. We can see the Fig. 2 where the spin independent direct DM detection cross-section allowed by the LUX [7] given by Red line corresponding to 5 GeV DM. The values above the Red line are not allowed by the LUX limit.

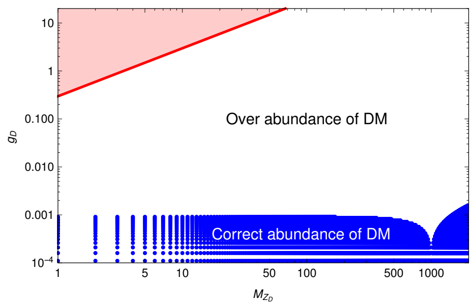

Figure 2: The LUX constraint on dark matter, arising via $Z - Z_D$ mixing, is shown on the plane of g_D versus M_{Z_D}.

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