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Co-genesis of matter and dark matter with vector-like fourth generation leptons

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ABSTRACT

We discuss aspects of a scenario for co-genesis of matter and dark matter which extends the standard model by adding a fourth generation vector-like lepton doublet and show that if the fourth neutrino is a massive pseudo-Dirac fermion with mass in the few hundred GeV range and mass splitting of about 100 keV, its lighter component can be a viable inelastic dark matter candidate. Its relic abundance is produced by the CP violating out-of-equilibrium decay of the type-II seesaw scalar triplet, which also gives rise to the required baryon asymmetry of the Universe via type-II leptogenesis, thus providing a simultaneous explanation of dark matter and baryon abundance observed today. Moreover, the induced vacuum expectation value of the same scalar triplet is responsible for the sub-eV Majorana masses to the three active neutrinos. A stable fourth generation of neutrinos is elusive at collider, however might be detected by current dark matter direct search experiments.

1. Introduction

Dark matter (DM), which constitutes 23% of the total energy budget of the Universe is currently supported by the rotation curve of galaxies and clusters, gravitational lensing and large scale structure of the Universe. These indirect evidences suggest that the DM should be massive, electrically neutral and stable on the cosmological time scale [1]. The only information about DM hitherto known is its relic abundance which is precisely measured by the Wilkinson Microwave Anisotropy Probe (WMAP) [2] and is given by $\Omega_{\rm DM}h^2 = 0.11$. However, the underlying mechanism which gives rise to the relic abundance is unknown.

It is usually presumed that a weakly interacting massive particle of mass $\mathcal{O}(100)$ GeV can be a good candidate for DM as its annihilation cross-section $\langle\sigma|v|\rangle \approx 3\times 10^{-26}$ cm^3/s satisfies the requirement of relic abundance, because it is produced by the standard thermal freeze-out mechanism [3]. However, an alternative mechanism has been explored in the literature, where the relic abundance of DM originates via the asymmetric component rather than the symmetric component of any stable species. In this case, the relic abundance depends on the amount of CP violation in the theory, in a similar way to the baryogenesis mechanism [4–39].

In this Letter we study the possibility of adding a vector-like lepton doublet to the standard model (SM) whose neutral member (to be called fourth neutrino henceforth) could be a candidate for DM. Indeed a fourth generation of fermions [40–46] is one of the simplest extension of physics beyond the SM with rich phenomenology and also extensively searched for at colliders. The properties of the new family are subject to tight constraints from electroweak precision measurements and by direct searches [47,48]. Considering the fourth generation leptons, probably the most stringent bound is the Z invisible width measured at LEP, because it provides strong evidence for only three families of light neutrinos. A fourth generation neutrino, if present, should be very distinct in nature from the three SM neutrinos. Indeed it should be heavier than at least $m_Z/2$, in order to avoid conflict with Z decay width measurement. Therefore the model of fourth generation leptons we present is distinct from the idea of sequential repetition of the SM fermionic families.

As is well known, in simple heavy fourth generation extensions of SM, the heavy neutrino (N_4), which is part of a lepton doublet $L_4 \equiv (N_4, E_4)$, does not qualify as a dark matter since rapid $N_4\bar{N}_4$ annihilation to SM particles via Z-exchange reduces its relic density to a value far below what is required for it to be a viable DM candidate as well as is excluded by direct DM searches due to its coupling with the Z boson. Our model for the fourth generation neutrino N_4 is however different: in addition to being part of a vector-like doublet, it has two additional features, which endow it with the properties that make it a viable dark matter candidate. (i) N_4 is a pseudo-Dirac neutrino, whose Majorana mass arises from the vev (vacuum expectation value) of a $Y = 2$ Higgs triplet Δ, acquired below electroweak (wk) phase

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transition. We will call this the type-II seesaw Higgs field, which anyway is present in our model to make the familiar active neutrinos acquire mass via the type-II seesaw mechanism. The presence of this Majorana mass makes it an inelastic dark matter [49], that has the advantage of fitting the results of current DM search experiments and not being excluded by upper limits. To keep the fourth family lepton doublet stable, we then impose an extra Z_2 symmetry on the model under which the fourth family lepton doublet L_4 is odd and all other fields of the theory are even [50,51]: besides the fourth family neutrino being lighter than the corresponding charged lepton, it is decoupled from the other lepton doublets. (ii) Secondly, the decay of the two type-II seesaw Higgs triplets via their CP violating coupling produces an asymmetry in the fourth family lepton number, which is large enough so that the depletion problem of relic density alluded to above does not occur. In fact, this asymmetry is comparable to the ordinary lepton number generated in the same decay which gives rise to the matter anti-matter asymmetry in the Universe via leptogenesis [50,51]. Both asymmetries can be comparable to each other in realistic models. In other words, the triplet mass scale is superheavy so that its CP violating out-of-equilibrium decay can produce asymmetry simultaneously in the DM and lepton sector and above the electroweak phase transition temperature, the lepton asymmetry for the familiar leptons gets converted to the baryon asymmetry via $SU(2)_L$ sphalerons [52]. In this case, we want to emphasize that the generated lepton asymmetry in the fourth generation does not get converted to baryon via sphaleron processes since L_4 being a vector-like doublet, it does not contribute to the $\mathrm{B}+\mathrm{L}$ anomaly of the standard model. On the other hand the symmetric component gets depleted via rapid annihilation, *i.e.* Z-exchange. The common origin of two asymmetries from the Δ decay then naturally explains the similar order of magnitude for the DM-to-baryon ratio and by adjusting the masses and couplings in both sectors, one can have $\Omega_{\mathrm{DM}}/\Omega_B \sim 5$. Thus our model provides another example of co-genesis of matter and dark matter.

It is worth mentioning that in this Letter we focus on the model building aspects of the co-genesis mechanism with respect to Refs. [50,51] and try to address some issues about the viability of the scenario described above that were left unexplored. In particular we propose a mechanism to introduce a splitting in mass between the neutral and charged partner of the vector-like doublet and we investigate the survival of the asymmetry at electroweak phase transition. Lastly we update the direct detection part with the latest data release by XENON100 [53], investigate if the model might accommodate the excess seen by the CRESST-II detector [54] and if there is a compatibility with the KIMS exclusion bound [55].

Our Letter is organized as follows. In Section 2 we present the model for a fourth generation of fermions, discussing in Section 4 constraints from electroweak precision measurements and direct searches at colliders. The phenomenology for generating the asymmetries and the measured DM-to-baryon ratio is presented in Section 3 together with the constraints from DM direct searches. We then summarize in Section 5.

2. Fourth generation pseudo-Dirac neutrino as DM

Fourth family neutrino has been studied as a dark matter in gauge extensions of the standard model by several authors [42,43,56,57]. In this study, we focus on a vector-like fourth generation lepton doublet, L_4, which will give a candidate of inelastic DM and being vector-like will not need the new set of quarks for anomaly cancellation.

2.1. Triplet seesaw and sub-eV Majorana masses of three active neutrinos

In addition to the vector-like lepton doublet, we add two scalar triplets $\Delta_{1,2}$ with $Y=2$. Since the hypercharge of Δ is 2, it can have bilinear coupling to Higgs doublet H as well as to the lepton doublets. The scalar potential involving Δ (from here on we drop the subscripts for the two scalar triplets and refer to them loosely as Δ) and H can be written as follows:

$$\begin{aligned} V(\Delta,H) = {} & M_\Delta^2 \Delta^\dagger\Delta + \frac{\lambda_\Delta}{2}\left(\Delta^\dagger\Delta\right)^2 - M_H^2 H^\dagger H \\ & + \frac{\lambda_H}{2}\left(H^\dagger H\right)^2 + \lambda_{\Delta H} H^\dagger H \Delta^\dagger \Delta \\ & + \frac{1}{\sqrt{2}}\left[\mu_H \Delta^\dagger H H + \text{h.c.}\right]. \end{aligned} \tag{1}$$

The bilinear couplings of leptons and Higgs to scalar triplet are given by

$$-\mathcal{L} \supset \frac{1}{\sqrt{2}}\left[f_H M_\Delta \Delta^\dagger H H + (f_L)_{\alpha,\beta} \Delta L_\alpha L_\beta + \text{h.c.}\right], \tag{2}$$

where $f_H = \mu_H/M_\Delta$ and $\alpha,\beta = 1,2,3$. Below electroweak phase transition the scalar triplet acquires an induced vev:

$$\langle\Delta\rangle = -f_H \frac{v^2}{\sqrt{2}M_\Delta}, \tag{3}$$

where $v = \langle H\rangle = 246$ GeV. The value of $\langle\Delta\rangle$ is upper bounded to be around 1 GeV in order not to spoil the SM prediction: $\rho \approx 1$. The $\Delta L_\alpha L_\beta$ coupling gives Majorana masses to three flavors of active neutrinos as

$$(M_\nu)_{\alpha\beta} = \sqrt{2} f_{\alpha\beta}\langle\Delta\rangle = -f_{L,\alpha\beta} f_H \frac{v^2}{\sqrt{2}M_\Delta}. \tag{4}$$

Taking $M_\Delta \sim 10^{10}$ GeV, $f_H \sim 1$ and $f_L \sim \mathcal{O}(10^{-4})$ we get $M_\nu \sim \mathcal{O}$ (eV), which is compatible with the observed neutrino oscillation data [58–60].

2.2. Triplet seesaw and pseudo-Dirac mass of fourth generation neutrino

The Lagrangian that gives the fourth family neutrino its mass is given by

$$-\mathcal{L}_{L_4\text{-}mass} = M_D \overline{L_4} L_4 + \frac{f_4}{\sqrt{2}} \overline{L_4^c} i\tau_2 \Delta L_4 + \text{h.c.} \tag{5}$$

where M_D generates the Dirac mass of the N_4. Below electroweak phase transition Δ acquires an induced vev and generates a Majorana mass $m = \sqrt{2} f_4\langle\Delta\rangle$ for N_4. Therefore, the Dirac spinor N_4 can be written as a sum of two Majorana spinors $(N_{4,L})$ and $(N_{4,R})$. As a result the Lagrangian (5) becomes:

$$\begin{aligned} -\mathcal{L}_{L_4\text{-}mass} = {} & M_D\left[\overline{(N_{4,L})}(N_{4,R}) + \overline{(N_{4,R})}(N_{4,L})\right] \\ & + m\left[\overline{(N_{4,L})^c}(N_{4,L}) + \overline{(N_{4,R})^c}(N_{4,R})\right]. \end{aligned} \tag{6}$$

This implies that there is a 2×2 mass matrix for the fourth generation neutrino in the basis $\{N_{4,L}, N_{4,R}\}$. By diagonalizing the mass matrix we get the two mass eigenstates N_1 and N_2 with mass eigenvalues $(M_D - m)$ and $(M_D + m)$. Thus the mass splitting between the two states is given by

$$\delta = 2m = 2\sqrt{2} f_4 \langle\Delta\rangle. \tag{7}$$