Right-handed sneutrino as cold dark matter of the universe

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Abstract. We consider the minimal supersymmetric standard model (MSSM) extended by three right-handed neutrinos. Assuming that neutrino masses are purely Dirac-type, the lightest right-handed sneutrino $\tilde{\nu}_R$ can be the lightest superparticle (LSP). We discuss the possibility that the LSP $\tilde{\nu}_R$ becomes dark matter of the universe, paying attention to the production of $\tilde{\nu}_R$ in the early universe. This work is based on collaboration with K. Ishiwata and T. Moroi [1, 2].

1. Introduction

The origin of dark matter (DM) is one of serious problems in particle physics and cosmology. Recently, the relic density of DM has been precisely determined by WMAP observations [3]

$$\Omega_{\text{DM}} h^2 = 0.105^{+0.007}_{-0.013},$$

where $h$ is the present Hubble constant in units of 100km/sec/Mpc. Since there is no candidate of DM in the Standard Model (SM), we need new physics beyond the SM. It has been widely discussed that supersymmetric model can provide a viable candidate of DM. The lightest superparticle (LSP) becomes completely stable with $R$-parity conservation, and can play a role of DM if it is neutral. The well-known candidate of the LSP DM is the lightest neutralino, and others include gravitino and axino.

In [1] we have proposed a possibility that the lightest right-handed sneutrino $\tilde{\nu}_R$ is the LSP DM. (Such a possibility has also been discussed recently in different context. See [4, 5].) This is motivated by very small but non-vanishing neutrino masses strongly suggested by the experimental evidences of neutrino oscillations. The non-zero neutrino masses require physics beyond the SM as well as the MSSM. The simplest way to generate neutrino masses is probably to introduce right-handed neutrinos (as well as sneutrinos in supersymmetric theories).

It has been widely discussed that right-handed (s)neutrinos are introduced together with their super-heavy Majorana masses which are much larger than the electroweak scale $\sim 100$ GeV. Then the smallness of neutrino masses is naturally explained by the so-called seesaw mechanism [6]. In this case, the right-handed sneutrino cannot be the LSP. On the other hand, if the neutrino masses are purely Dirac-type, the mass of right-handed sneutrino is $\sim 100$ GeV and can be the LSP. Moreover, as we will explain below, the relic density of the LSP $\tilde{\nu}_R$ can be consistent with (1), and $\tilde{\nu}_R$ is a viable candidate of DM of the universe.
2. Model

We consider the MSSM with three right-handed neutrinos assuming that neutrino masses are purely Dirac-type. The superpotential is then given by

\[ W = W_{\text{MSSM}} + y_\nu \hat{H}_u \hat{L} \bar{\nu}_R, \]

where \( W_{\text{MSSM}} \) is the MSSM superpotential and \( y_\nu \) denotes the neutrino Yukawa couplings. Here and hereafter, the generation indices are implicit. Further, we introduce tri-linear couplings of \( \bar{\nu}_R \) which will be important in the discussion below: \( \mathcal{L} = a_\nu y_\nu m_{\tilde{L}} H_u \bar{\nu}_R + h.c. \), where \( m_{\tilde{L}} \) is the soft mass for slepton doublet.

In this model, neutrino masses come only from electroweak symmetry breaking as \( m_\nu = y_\nu \langle H_u^0 \rangle = y_\nu v \sin \beta \), where \( v \simeq 174 \text{ GeV} \) and \( \tan \beta = \langle H_d^0 \rangle / \langle H_u^0 \rangle \). Thus, \( y_\nu \) is determined once \( m_\nu \) is fixed:

\[ y_\nu \sin \beta \simeq 3.0 \times 10^{-13} \times \left( \frac{m_\nu^2}{2.8 \times 10^{-3} \text{ eV}^2} \right)^{1/2}. \]

We can see that neutrino mass scales in oscillation experiments leads to very small \( y_\nu \). One might think that such small couplings are unnatural. However, it is indeed natural in the 't Hooft sense [7], since chiral symmetry of neutrino is restored in the limit of vanishing Yukawa couplings.

In the considering model, right-handed sneutrinos receive masses dominantly from the effects of supersymmetry breaking. (Here we consider gravity-mediation models of supersymmetry breaking.) Then, one should note that the lightest right-handed sneutrino \( \tilde{\nu}_R \) can be the LSP. Since \( \tilde{\nu}_R \) is neutral, is stable under the R-parity conservation, and also is very weakly interacting, it can be a good candidate of DM provided that its relic density \( \Omega_{\tilde{\nu}_R} \) is the right amount (1).

3. Right-handed sneutrino as cold dark matter

Now we discuss the production of \( \tilde{\nu}_R \) in the early universe. We should note that \( \tilde{\nu}_R \) is not thermalized due to the smallness of \( y_\nu \) (3). It has been found that \( \tilde{\nu}_R \) is effectively produced by decays of superparticles [1, 2], and that there are two distinct contributions: \( \Omega_{\tilde{\nu}_R} = \Omega_{\tilde{\nu}_R}^{\text{CE}} + \Omega_{\tilde{\nu}_R}^{\text{FO}} \)

where \( \Omega_{\tilde{\nu}_R}^{\text{CE}} \) is due to decays of various superparticles in chemical equilibrium, while \( \Omega_{\tilde{\nu}_R}^{\text{FO}} \) due to decay of the NLSP after freeze-out.

We first consider \( \Omega_{\tilde{\nu}_R}^{\text{CE}} \). As shown in [1], it can be estimated by solving the Boltzmann equation for the number density of \( \tilde{\nu}_R \). Since the rates of superparticle decays into \( \tilde{\nu}_R \) are proportional to \( y_\nu^2 \), and hence \( \Omega_{\tilde{\nu}_R}^{\text{CE}} \propto y_\nu^2 \). The dominant production occurs when the temperature is comparable to the superparticle mass. There are various processes which produce \( \tilde{\nu}_R \). Among them, decay of Higgsino dominates when the effects of the tri-linear scalar couplings are negligible. In this case, we have found that \( \Omega_{\tilde{\nu}_R}^{\text{CE}} \sim 10^{-2} \Omega_{\text{DM}} \) and is too small to explain the DM relic density. However, we have also found that the production of \( \tilde{\nu}_R \) is enhanced in some cases.

One possibility occurs when the mass of left-handed sneutrino is close to \( m_{\tilde{\nu}_R} \). In this case, the left-right mixing angle of sneutrinos becomes larger, which enhance the decay of wino into \( \tilde{\nu}_R \). In Fig. 1 we show \( \Omega_{\tilde{\nu}_R}^{\text{CE}} h^2 \) as a function of \( m_{\tilde{\nu}_L} \) when \( m_{\tilde{\nu}_R} = 100 \text{ GeV}, m_{\tilde{\nu}_R} = 300 \text{ GeV} \) and \( \mu_H = 150 \text{ GeV} \). We can see that \( \Omega_{\tilde{\nu}_R}^{\text{CE}} \simeq \Omega_{\text{DM}} \) is obtained with the mass degeneracy of \( \sim 10\% \) for \( |a_\nu| \sim 3 \). Therefore, if this is the case, \( \tilde{\nu}_R \) dark matter suggests the light \( \tilde{\nu}_L \), which will be a good target for future collider experiments. Even without mass degeneracy between \( \tilde{\nu}_R \) and \( \tilde{\nu}_L \), \( \Omega_{\tilde{\nu}_R}^{\text{CE}} \simeq \Omega_{\text{DM}} \) is realized when \( |a_\nu| \gg 1 \). Although such a large value of \( |a_\nu| \) may not be obtained in simple supergravity models, it is phenomenologically viable.

Another possibility is due to degenerate neutrinos which are allowed from the data of oscillation experiments. As mentioned above, the larger neutrino masses enhance \( \Omega_{\tilde{\nu}_R}^{\text{CE}} \). Indeed,
Figure 1. The relic density $\Omega_{\tilde{\nu}_R}^{\text{CE}} h^2$ as a function of $m_{\tilde{\nu}_L}$. The solid and dashed lines correspond to the cases with and without the thermal mass of $\tilde{\nu}_L$, respectively. We take $a_\nu = 1, 3, 5$ from left to right. Here $m_{\tilde{\nu}_R} = 100$ GeV, $m_{\tilde{\nu}_R} = 300$ GeV and $\mu_H = 150$ GeV. The horizontal dot-dashed lines correspond to the dark-matter density (1).

$\Omega_{\tilde{\nu}_R}^{\text{CE}} \simeq \Omega_{\text{DM}}$ is obtained when $m_\nu \sim 0.1$ eV. Such a range of $m_\nu$ might be verified in future astrophysical observations of cosmic structures.

Next, we turn to consider $\Omega_{\tilde{\nu}_R}^{\text{FO}}$. The NLSP, which is assumed to be the LSP in the MSSM sector in this analysis, is very long-lived because of the smallness of $y_\nu$ (3). Then, the NLSP decays after its freeze-out time, which gives alternative source of $\tilde{\nu}_R$. The contribution to the relic density via this mechanism is given by $\Omega_{\tilde{\nu}_R}^{\text{FO}} = (m_{\tilde{\nu}_R}/m_{\text{NLSP}})\Omega_{\text{NLSP}}$. Here $\Omega_{\text{NLSP}}$ is the “would-be” present density of the NLSP for the case when the NLSP is stable. Since $\Omega_{\text{NLSP}}$ is determined by physics around the freeze-out time, $\Omega_{\tilde{\nu}_R}^{\text{FO}}$ is also insensitive physics for $T \gg 100$ GeV. Although $\Omega_{\text{NLSP}}$ is very sensitive to the MSSM parameters, it can be larger than $\Omega_{\text{DM}}$ leading to $\Omega_{\tilde{\nu}_R}^{\text{FO}} \simeq \Omega_{\text{DM}}$. In such a parameter space, the $\tilde{\nu}_R$ DM can be realized. Indeed, we have illustrated this possibility by using the minimal supergravity model in [2]. We should note that the late decay of the NLSP might destroy the success of the BBN. As explained in [2], although the decay of the bino-like NLSP is almost harmless, while that of the stau NLSP is severely restricted. To avoid the BBN constraint the NLSP lifetime must be short enough, which may suggest the degenerate neutrinos and/or the large left-right mixing of sneutrinos.

Finally, we notice that, even if Majorana masses for right-handed neutrinos are present, $\tilde{\nu}_R$ can be the LSP. In this case, however, $y_\nu$ becomes larger which results in the universe overclosed by $\tilde{\nu}_R$. To avoid this difficulty, the reheating temperature should be so low that superparticles cannot be thermalized. (See also [4].)

4. Summary
We have discussed the MSSM with three right-handed (s)neutrinos assuming that neutrino masses are purely Dirac-type. We have shown that the lightest right-handed sneutrino $\tilde{\nu}_R$ with mass $m_{\tilde{\nu}_R} \sim 100$ GeV can be the LSP, and that the relic density of $\tilde{\nu}_R$ can be consistent with $\Omega_{\text{DM}}$. Thus, the LSP $\tilde{\nu}_R$ is a good candidate for cold dark matter of the universe.

References
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