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Supersymmetric Higgs-portal and X-ray lines

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ABSTRACT

We consider a Dirac singlet fermion as thermal dark matter for explaining the X-ray line in the context of a supersymmetric Higgs-portal model or a generalized Dirac NMSSM. The Dirac singlet fermion gets a mass splitting due to their Yukawa couplings to two Higgs doublets and their superpartners, Higgsinos, after electroweak symmetry breaking. We show that a correct relic density can be obtained from thermal freeze-out, due to the co-annihilation with Higgsinos for the same Yukawa couplings. We discuss the phenomenology of the Higgsinos in this model such as displaced vertices at the LHC.

1. Introduction

Dark matter (DM) is a main component of matter in the Universe, confirmed by various observations such as galaxy rotation curves, gravitational lensing. Moreover, it is supported by the measurement of Cosmic Microwave Background Radiation and Large Scale Structure, and so on. However, we have no clue as to the DM mass and interactions other than gravity. Therefore, direct detection on earth, indirect detection in the sky, and direct production at particle colliders have been thought to be complementary for identifying the nature of DM. In particular, indirect detections look for the remnants of annihilations or decays of DM through cosmic rays coming from galaxies and galaxy clusters.

There has recently been a lot of interest in light DM models, after new detection of X-ray line coming from galaxies and galaxy clusters mainly by the XMM-Newton observatory [1,2]. There are on-going debates on the possibility of explaining the X-ray line excess with thermal atomic transition [3] and no line signal has been observed from other systems such as dwarf satellites of the Milky Way [4]. Nonetheless, until the excess is confirmed or ruled out by another experiment, it is worthwhile to take it to be a signal for DM and study the consequences of decaying or annihilating DM models [5–8].

Motivated by a toy model suggested by one of us [6], we consider a concrete model for explaining the X-ray line with the magnetic dipole moment of a weakly interacting massive particle (WIMP) in the context of a generalized next-to-minimal supersymmetric standard model (NMSSM) with an additional Dirac singlet superfield, dubbed as Dirac NMSSM [9,10]. Unlike the toy model where a discrete Z_2 symmetry for stabilizing DM is broken by a small amount at the cutoff scale [6], the corresponding discrete parity, i.e. R-parity, in the supersymmetric (SUSY) version is assumed to be exact. Then, a singlet Dirac fermion or two Majorana fermions called the singlinos, introduced in the Dirac NMSSM, is the DM candidate, and it gets a small mass splitting for the X-ray line energy at 3.55 keV due to its small Yukawa couplings to the MSSM Higgses and their superpartners. In this case, a tiny magnetic transition dipole moment for decaying DM generates the X-ray line by the small Yukawa couplings of the singlinos. We regard the model as a SUSY Higgs-portal in the limit that gauginos, squarks and sleptons are heavy enough. We also include the effects of non-decoupled gauginos on the mass splitting of Higgsinos or singlinos. The lightness of Higgsinos and singlinos can be ensured by a chiral symmetry such as Peccei–Quinn symmetry while gauginos could be relatively light due to R-symmetry.

The Dirac singlet fermion can keep in thermal equilibrium with the Standard Model (SM) particles at freeze-out, due to the co-annihilation with the Higgsino-like fermions. Consequently, we show that the correct relic density can be attained, being compat-

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ible with the X-ray line. In the limit of heavy gauginos, the mass splitting of Higgsino states is about keV scale as for the singlino fermions, so neutral or charged Higgsinos decay into a singlino $+Z^*/W^*$, leaving a displaced vertex due to small Yukawa couplings of singlinos. We discuss the possibility of discovering Higgsinos at the LHC in this new topology.

The paper is organized as follows. We begin with the model description of the SUSY Higgs-portal for the low-energy mass spectra of DM and Higgsinos. Then, we present the results of the magnetic transition dipole moment between two singlinos at one loop in our model and show the parameter space that is consistent with both the energy and flux for the X-ray line. In turn, we discuss the bound from the DM relic density and its compatibility with the X-ray line. Finally, conclusions are drawn.

2. Supersymmetric Higgs-portal

The dark sector couples to the SM particles only through the Higgs and its superpartners. As an example, we consider an extension of the Higgs sector in the MSSM with a Dirac singlet chiral superfield containing two additional singlet superfields, S and $\bar{S}$. We assume that the gauginos as well as the superpartners of quarks and leptons are sufficiently heavy so that they are not relevant for our discussion. Meanwhile, we also discuss the effects of non-decoupled gauginos in this section.

The part of the superpotential containing only Higgs doublets, H_u and H_d, and the singlet chiral superfields are

$$W_0 = \lambda_S S H_u H_d + \lambda_{\bar{S}} \bar{S} H_u H_d + M_S S\bar{S} + \mu_H H_u H_d + \mu_S S + \mu_{\bar{S}} \bar{S}. \tag{1}$$

In this model, the Dirac singlet chiral superfield communicates with the SM only through the Higgs and Higgsino interactions. As for the Dirac singlino, the model can also be called the Higgsino portal. In a Peccei–Quinn (PQ) symmetric realization of the above superpotential, the cubic couplings for the singlet chiral superfields are forbidden, while the bare Higgsino and singlino mass terms and the singlet tadpole terms can be generated after a spontaneous breaking of the PQ symmetry by non-renormalizable interactions with PQ-breaking fields.

When there is a $U(1)_S$ global symmetry or a Z_2 symmetry distinguishing S and $\bar{S}$, the operator $\bar{S}H_u H_d$ is forbidden. This case corresponds to the Dirac NMSSM that was discussed in Refs. [9, 10], where even after integrating out the singlet scalar masses with keeping their fermion partners, the resulting Higgs potential gets an additional quartic potential, $|\lambda_S H_u H_d|^2$, and increases the Higgs mass as compared to the MSSM. When the singlet symmetry is broken spontaneously or explicitly, we can write a small Yukawa coupling for $\bar{S}$ such that $|\lambda_{\bar{S}}| \ll |\lambda_S| = \mathcal{O}(1)$. Then, the feature of the Dirac NMSSM for the Higgs mass can be maintained.

On the other hand, if $|\lambda_S|$ and $|\lambda_{\bar{S}}|$ are comparable, the PQ symmetry only does not distinguish between S and $\bar{S}$. Thus, there is no obvious reason to forbid Majorana mass terms such as S^2 and $\bar{S}^2$ in the superpotential. But, if we ignore those Majorana mass terms under the assumption that such a flavor structure in the dark sector is determined by a flavor symmetry for singlinos at a high energy scale, we can explain a small mass splitting and a small flux required for the X-ray line for $|\lambda_S|$, $|\lambda_{\bar{S}}| \ll 1$, as will be discussed in the next section.

The neutralino mass matrix containing the gauginos in MSSM is given in the basis $(\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0, \widetilde{S}, \widetilde{\bar{S}})$ by

$$M_{\widetilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g' v_d & \frac{1}{2}g' v_u & 0 & 0 \\ 0 & M_2 & \frac{1}{2}g v_d & -\frac{1}{2}g v_u & 0 & 0 \\ -\frac{1}{2}g' v_d & \frac{1}{2}g v_d & 0 & -\mu_{\rm eff} & -\frac{1}{\sqrt{2}}\lambda_S v_u & -\frac{1}{\sqrt{2}}\lambda_{\bar{S}} v_u \\ \frac{1}{2}g' v_u & -\frac{1}{2}g v_u & -\mu_{\rm eff} & 0 & -\frac{1}{\sqrt{2}}\lambda_S v_d & -\frac{1}{\sqrt{2}}\lambda_{\bar{S}} v_d \\ 0 & 0 & -\frac{1}{\sqrt{2}}\lambda_S v_u & -\frac{1}{\sqrt{2}}\lambda_S v_d & 0 & M_S \\ 0 & 0 & -\frac{1}{\sqrt{2}}\lambda_{\bar{S}} v_u & -\frac{1}{\sqrt{2}}\lambda_{\bar{S}} v_d & M_S & 0 \end{pmatrix}, \tag{2}$$

where $v_u^2 + v_d^2 = v^2 \simeq (246\ \text{GeV})^2$, $\tan\beta = v_u/v_d$, and the effective μ parameter is given by $\mu_{\rm eff} = \mu_H + \lambda_S\langle S\rangle + \lambda_{\bar{S}}\langle \bar{S}\rangle$.

In order to keep a small mass splitting between singlinos, we take the gauginos to be much heavier than Higgsinos and singlinos, namely, $M_{1,2} \gg \mu_{\rm eff}, M_S$. Then, we can consider only the 4×4 sub-matrix for Higgsinos and singlinos and a mass splitting of the Dirac singlinos is attributed to a small coupling between Higgsinos and singlinos. Then, keeping all the other superpartners of the SM heavy enough, we can call the model the SUSY Higgs-portal.

In the limit of $M_{1,2} \gg \mu_{\rm eff}, M_S$, the mass eigenvalues for Higgsino-like neutralinos are

$$\begin{aligned} m_{\widetilde{\chi}_1^0} &= \mu_{\rm eff} - \frac{1}{8}(v_u + v_d)^2 \\ &\quad \times \left(\frac{g'^2(M_1 - 2\mu_{\rm eff})}{(M_1 - \mu_{\rm eff})^2} + \frac{g^2(M_2 - 2\mu_{\rm eff})}{(M_2 - \mu_{\rm eff})^2} \right), \\ m_{\widetilde{\chi}_2^0} &= \mu_{\rm eff} + \frac{1}{8}(v_u - v_d)^2 \\ &\quad \times \left(\frac{g'^2(M_1 + 2\mu_{\rm eff})}{(M_1 + \mu_{\rm eff})^2} + \frac{g^2(M_2 + 2\mu_{\rm eff})}{(M_2 + \mu_{\rm eff})^2} \right), \end{aligned} \tag{3}$$

while those for singlino-like neutralinos are, for $\lambda_S, \lambda_{\bar{S}} \ll 1$,

$$\begin{aligned} m_{\widetilde{\chi}_3^0} &= M_S + \frac{1}{8}(\lambda_S - \lambda_{\bar{S}})^2 \left(\frac{(v_u - v_d)^2}{\mu_{\rm eff} + M_S} - \frac{(v_u + v_d)^2}{\mu_{\rm eff} - M_S} \right) \\ &\quad + \frac{1}{16}(\lambda_S - \lambda_{\bar{S}})^2 \frac{(v_u^2 - v_d^2)^2 \mu_{\rm eff}^2}{(\mu_{\rm eff}^2 - M_S^2)^2} \\ &\quad \times \left(\frac{g'^2(M_1 + 2M_S)}{(M_1 + M_S)^2} + \frac{g^2(M_2 + 2M_S)}{(M_2 + M_S)^2} \right), \\ m_{\widetilde{\chi}_4^0} &= M_S + \frac{1}{8}(\lambda_S + \lambda_{\bar{S}})^2 \left(\frac{(v_u + v_d)^2}{\mu_{\rm eff} + M_S} - \frac{(v_u - v_d)^2}{\mu_{\rm eff} - M_S} \right) \\ &\quad - \frac{1}{16}(\lambda_S + \lambda_{\bar{S}})^2 \frac{(v_u^2 - v_d^2)^2 \mu_{\rm eff}^2}{(\mu_{\rm eff}^2 - M_S^2)^2} \\ &\quad \times \left(\frac{g'^2(M_1 - 2M_S)}{(M_1 - M_S)^2} + \frac{g^2(M_2 - 2M_S)}{(M_2 - M_S)^2} \right). \end{aligned} \tag{4}$$

Consequently, the mass differences between the nearest neutralinos are

$$\begin{aligned} \Delta m_{21} &\equiv m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0} \\ &\approx \frac{1}{4} v^2 \left(\frac{g'^2}{M_1} + \frac{g^2}{M_2} \right), \end{aligned} \tag{5}$$

and

$$\begin{aligned} \Delta m_{34} &\equiv m_{\widetilde{\chi}_3^0} - m_{\widetilde{\chi}_4^0} \\ &\approx \frac{1}{2} \frac{v^2}{\mu_{\rm eff}^2 - M_S^2} \Big((\lambda_+^2 - \lambda_-^2) M_S - (\lambda_+^2 + \lambda_-^2)\mu_{\rm eff} \sin(2\beta) \Big) \\ &\quad + \frac{1}{8}(\lambda_+^2 + \lambda_-^2) \frac{v^4 \cos^2(2\beta)\mu_{\rm eff}^2}{(\mu_{\rm eff}^2 - M_S^2)^2} \left(\frac{g'^2}{M_1} + \frac{g^2}{M_2} \right), \end{aligned} \tag{6}$$