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Singlino-dominated lightest supersymmetric particle as a CDM candidate in supersymmetric models with an extra U(1)

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We consider a singlino-dominated neutralino in supersymmetric models with an extra U(1). In case both the μ term and also the Z' mass are generated by the vacuum expectation value of the scalar component of the same singlet chiral superfield, generically the lightest neutralino is not expected to be dominated by the singlino. However, if the gaugino corresponding to the extra U(1) is sufficiently heavy, the lightest neutralino can be dominated by the singlino and still satisfy the constraints resulting from the Z' phenomenology. We assume a supersymmetry breaking scenario in which the extra U(1) gaugino can be much heavier than other gauginos. In that framework we show that the singlino-dominated lightest neutralino may be a good candidate for dark matter in a parameter space where various phenomenological constraints are satisfied.

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I. INTRODUCTION

Various astrophysical observations seem to confirm the existence of a substantial amount of nonrelativistic and nonbaryonic dark matter [1,2]. The amount of cold dark matter (CDM) has been estimated to be $\Omega_{\rm CDM}h^2 = 0.12 \pm 0.01$ through combined analyses of the Solan Digital Sky Survey (SDSS) data on the large scale structure and the Wilkinson Microwave Anisotropy Probe (WMAP) data. This fact suggests that the Standard Model (SM) of Elementary Particle Physics is required to be extended to include a CDM candidate.

Supersymmetric extensions of the SM have been considered to be the most promising candidate for a solution to the gauge hierarchy problem [3]. It is interesting that supersymmetric models can naturally contain a CDM candidate. If the R parity is conserved, the lightest neutral supersymmetric particle (LSP) is stable and then can be a good candidate for the CDM. The most promising particle to play such a role is the lightest neutralino. Relic density of the thermally produced lightest neutralino is determined by its density at freeze-out temperature T_F. It is estimated by $H(T_F) \simeq \langle\sigma_{\rm ann}v\rangle n_\chi(T_F)$, where $H(T_F)$ is the Hubble parameter at T_F and $\langle\sigma_{\rm ann}v\rangle$ is thermal average of annihilation cross section times relative velocity of neutralinos [4]. Since neutralino χ has mass of the order of the weak scale and feels only the weak interaction, we can generally expect its energy density Ω_χ to be $O(1)$. Detailed analyses of this relevant quantity have been extensively done, especially, in the minimal supersymmetric standard model (MSSM) [5]. In both frameworks of the minimal supergravity and the constrained MSSM, many works have shown that the relic neutralino abundance can accommodate the observed $\Omega_{\rm CDM}h^2$ as long as model parameters are suitably selected [6–8].

Although the MSSM is today the best candidate to describe physics beyond the SM, it has certain weak points too. Among them is the well known μ problem. The next to the MSSM (NMSSM) [9] and the models with an extra U(1) [10,11] have been proposed as elegant solutions of the μ problem. In both cases an SM singlet chiral superfield $\hat{S}$ is introduced and superpotential is extended by a term $\lambda\hat{S}\hat{H}_1\hat{H}_2$.[1] The μ term $\mu\hat{H}_1\hat{H}_2$ is generated as $\mu = \lambda\langle S\rangle$, i.e. by a vacuum expectation value of the scalar component of $\hat{S}$ through the introduced operator. A difference between the two models appears in the way a bare term $\mu\hat{H}_1\hat{H}_2$ is forbidden and the potential for S is stabilized. Related to these issues, a cubic term $\kappa\hat{S}^3$ and an extra U(1) have been introduced in each case, respectively. It is worth noting that there is a cosmological domain wall problem in the former case, which can be escaped by introducing suitable nonrenormalizable operators [12]. However, the models with an extra U(1) do not have such a problem. Moreover the models with an extra U(1) often appear as the effective theory of superstring. They generally contain exotic fields [13]. Since the Higgs and the neutralino sector in both the NMSSM and the models with an extra U(1) are extensions of those of the MSSM, the relic density of the lightest neutralino is expected to show different features from the corresponding one in the MSSM. Since these models have various interesting new

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[1] In this paper we put a hat on the character describing a superfield. For its component fields, we put a tilde on the same character for superpartners of the SM fields and use just the same character without the hat for the SM fields. Otherwise, the field without a tilde should be understood as a scalar component.

aspects as the extensions of the MSSM, it is worth studying them in detail on the basis of the WMAP data.

In Ref. [14] the relic density of the lightest neutralino in the NMSSM has been studied and its compatibility with the WMAP results has been discussed in detail. Since the Higgs sector is extended by scalar and pseudoscalar components of the singlet chiral superfield $\hat{S}$ as compared with the MSSM, annihilation of the lightest neutralino can have various effective modes. As the result, the WMAP constraint can be satisfied easier in the NMSSM than in the MSSM. This happens in various cases such that the lightest neutralino is the binolike LSP, the bino-Higgsino mixed LSP and the singlinolike LSP. In particular, the singlinolike LSP is shown to annihilate effectively by the effects of additional couplings $\lambda\hat{S}\hat{H}_1\hat{H}_2$ and $\kappa\hat{S}^3$. The singlino LSP is found to satisfy the constraint from the relic density although it has no SM interactions. The neutralino relic density has also been examined in the modified NMSSM (nMSSM) where the cubic term $\kappa\hat{S}^3$ is replaced by a linear term of $\hat{S}$ [15].

The relic density of the lightest neutralino in a model with an extra U(1) has already been studied in [16]. Since the neutralino sector is extended as compared with the MSSM by a fermionic component $\tilde{S}$ and also an extra U(1) gaugino $\tilde{\lambda}_x$, the features of the neutralinos can be different from the corresponding ones in both the MSSM and the NMSSM [16,17]. In particular, if the singlino $\tilde{S}$ dominates the lightest neutralino, a large change is expected to appear in the neutralino phenomenology. The relic density needs to be studied by taking account of such a situation. In the simple models with an extra U(1), the extra U(1) symmetry is supposed to be broken by a vacuum expectation value $\langle S\rangle$, which gives the origin of the μ term. The lightest neutralino dominated by the singlino component is expected to occur when $\langle S\rangle$ takes a value of the order of the weak scale as long as λ is not so small.[2] In the NMSSM such a value of $\langle S\rangle$ brings no problem and the singlino-dominated LSP can realize the CDM abundance as discussed in [14]. In the models with an extra U(1), however, there exist severe constraints on $\langle S\rangle$ resulting from the mass of the extra U(1) gauge boson Z' and its mixing with the ordinary Z boson based on the direct search and the electroweak precision measurements [18,19]. These constraints tend to require that $\langle S\rangle$ should be more than $O(1)$ TeV as long as we do not consider a special situation.[3] Thus, we cannot expect a substantial difference in the lightest neutralino sector from the MSSM since both $\tilde{S}$ and $\tilde{\lambda}_x$ practically decouple from the lightest neutralino. Here it is useful to note that the lightest neutralino can be dominated by the singlino even in this kind of models with an extra U(1) if the gaugino $\tilde{\lambda}_x$ can be very heavy. In that case we may have the lightest neutralino as a candidate for the CDM, which has a very different nature from that in both the MSSM and the NMSSM. From this point of view, the relic density of the lightest neutralino has been studied in [16].

In the models with an extra U(1) the singlino-dominated lightest neutralino feels the extra U(1) gauge interaction. Thus, it can annihilate through the s-channel exchange of Z' even if it is dominated by the singlino. Unfortunately, the result in [16] seems to show that the WMAP constraint cannot be satisfied by the singlinolike LSP if we impose the currently known lower bound for the Z' mass. However, their analysis has been done for the case that the lightest neutralino is composed of 81% singlino and 12.5% Higgsinos $\tilde{H}_{1,2}$ as a typical example. If we assume that the extra U(1) gaugino $\tilde{\lambda}_x$ can be much heavier and the lightest neutralino is almost dominated by the singlino, its annihilation is expected to be enhanced since the extra U(1) charge of the singlino $\tilde{S}$ can be generally larger than the Higgsinos $\tilde{H}_{1,2}$, as will be discussed later. From this viewpoint, it seems worth reanalyzing this possibility by assuming much larger mass for $\tilde{\lambda}_x$ than the one assumed in [16]. The lightest neutralino may have very small mass, which is forbidden in the MSSM already. However, if it is dominated by the singlino, it can be expected to escape the current experimental constraints and be a good CDM candidate. Since the models with an extra U(1) are the interesting extension of the MSSM, it will be useful to reexamine the inherent possibility in such models.

This paper is organized as follows. In Sec. II we briefly review the features of the models with an extra U(1) and discuss their neutralino sector in the case of a heavy extra U(1) gaugino $\tilde{\lambda}_x$. In Sec. III we study numerically the features of the lightest neutralino and also estimate the relic abundance of the lightest neutralino in that case. Then we examine the compatibility with the WMAP constraints. Section IV is devoted to the summary. In the Appendix we present an example for the supersymmetry breaking scenario, which can realize the assumed possibility of nonuniversal mass only for the Abelian gaugino.

II. MODELS WITH LARGE ABELIAN GAUGINO MASS

We consider the models with an extra U(1), which contain a very heavy extra U(1) gaugino and can give a solution to the μ problem. We assume that the extra U(1) gauge symmetry is broken by the vacuum expectation value $\langle S\rangle$ of the scalar component of the SM singlet chiral

[2] In the NMSSM the singlino domination of the LSP for a larger value of $\langle S\rangle$ is also studied in [14]. There it is shown that even in that case the singlinolike LSP is possible for a very small λ.

[3] Even in the extra U(1) models, if one considers a model with a secluded singlet sector, which is called the S-model in [20], $\langle S\rangle$ can take a value of the weak scale. In this case phenomenological features at the weak scale are very similar to the NMSSM with a weak scale $\langle S\rangle$.

superfield $\hat{S}$. The μ term is considered to be generated through an operator in the superpotential of the form

$$W_{\rm ob} = \lambda \hat{S}\hat{H}_1\hat{H}_2 + \ldots, \tag{1}$$

where $\hat{H}_{1,2}$ are the ordinary doublet Higgs chiral superfields and a coupling constant λ is assumed to be real. This superpotential requires that $\hat{H}_{1,2}$ also have extra U(1) charges $Q_{1,2}$, which satisfy a charge conservation condition

$$Q_1 + Q_2 + Q_S = 0. \tag{2}$$

As a result of this feature, if the scalar components of $\hat{H}_{1,2}$ and $\hat{S}$ obtain the vacuum expectation values defined by

$$\langle H_1\rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \qquad \langle H_2\rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \qquad \langle S\rangle = u, \tag{3}$$

the neutral gauge bosons Z_μ and Z'_μ mix with each other. This mixing can be represented by a mass matrix $M_{ZZ'}$ as [10,19]

$$\begin{pmatrix} \frac{g_W^2+g_Y^2}{2}v^2 & \frac{g_x\sqrt{g_W^2+g_Y^2}}{2}v^2(Q_1\cos^2\beta - Q_2\sin^2\beta) \\ \frac{g_x\sqrt{g_W^2+g_Y^2}}{2}v^2(Q_1\cos^2\beta - Q_2\sin^2\beta) & \frac{g_x^2}{2}v^2(Q_1^2\cos^2\beta + Q_2^2\sin^2\beta + Q_S^2\frac{u^2}{v^2}) \end{pmatrix} \tag{4}$$

where we use the basis (Z_μ, Z'_μ) and $v^2 = v_1^2 + v_2^2$ and $\tan\beta = v_2/v_1$. An extra U(1) charge Q_f and a coupling g_x are defined through the covariant derivative

$$D_\mu = \partial_\mu + i\frac{\tau^3}{2}g_W W_\mu^3 + i\frac{Y_f}{2}g_Y B_\mu + i\frac{Q_f}{2}g_x Z'_\mu. \tag{5}$$

Mass eigenvalues of these neutral gauge bosons can be expressed as

$$\begin{aligned} m_{Z_1}^2 &\simeq m_Z^2 - m_Z^2\frac{g_x\tan2\xi}{\sqrt{g_W^2+g_Y^2}}(Q_1\cos^2\beta - Q_2\sin^2\beta), \\ m_{Z_2}^2 &\simeq \frac{g_x^2}{2}(Q_1^2v_1^2 + Q_2^2v_2^2 + Q_S^2u^2) \\ &\quad + m_Z^2\frac{g_x\tan2\xi}{\sqrt{g_W^2+g_Y^2}}(Q_1\cos^2\beta - Q_2\sin^2\beta), \end{aligned} \tag{6}$$

where m_Z is the Z boson mass in the SM and ξ is a ZZ' mixing angle.

Direct search for the new neutral gauge boson and precise measurements of the electroweak interactions constrain the mass eigenvalue m_{Z_2} of the new gauge boson and the ZZ' mixing angle ξ. These conditions may be summarized as $m_{Z_2} \gtrsim 600$ GeV and $\xi \lesssim 10^{-3}$ [18],[4] which constrain the value of u directly and also the value of λ indirectly through the relation $\mu = \lambda u$. The value of μ is restricted by the chargino mass bound and also the electroweak symmetry breaking condition [10,11]. It is useful to note that the ZZ' mixing constraint disappears for a special case $\tan\beta \simeq \sqrt{Q_1/Q_2}$. In this case we can regard the lower bound of u as the one which comes from the direct search of Z'. Moreover, since $Q_1Q_2 > 0$ should be satisfied, the charge conservation (2) for the extra U(1) makes $|Q_S|$ a larger value than other Higgsino charges $|Q_{1,2}|$. Since the interaction of the singlino with Z' can be larger compared with that of $\tilde{H}_{1,2}$, the annihilation of the singlinolike LSPs through the s-channel exchange of Z' will be enhanced as the singlino component in the LSP increases. Although this situation may require tuning of supersymmetry breaking parameters, it may bring interesting phenomenology different from that of the MSSM. Thus in the following study, we consider the situation approximated by this special condition as the first step and we only impose the constraint $m_{Z_2} \geq 600$ GeV.

In this model the neutralino sector is extended into six components, since there are two additional neutral fermions $\tilde{\lambda}_x$ and $\tilde{S}$ compared with the MSSM. If we take the canonically normalized gaugino basis $\mathcal{N}^T = (-i\tilde{\lambda}_x, -i\tilde{\lambda}_W^3, -i\tilde{\lambda}_Y, \tilde{H}_1, \tilde{H}_2, \tilde{S})$ and define the neutralino mass term as $\mathcal{L}^m_{\rm neutralino} = -\frac{1}{2}\mathcal{N}^T\mathcal{M}\mathcal{N} +$ h.c., the 6×6 neutralino mass matrix $\mathcal{M}$ can be represented as[5]

[4]This bound for m_{Z_2} obtained from the Z' decay into the dilepton pairs depends on the models. It can be relaxed if Z' has a substantial decay width into non-SM fermion pairs such as neutralino pairs [21]. This is expected to occur in the case that the singlino-dominated neutralino is light enough to make this decay mode possible and has a larger coupling with Z' compared with the electrons. We will comment on this point later.

[5]Kinetic term mixing between two Abelian vector superfields is not considered here. The study of their phenomenological effects can be found in [17].

$$\begin{pmatrix} M_x & 0 & 0 & \frac{g_x Q_1}{\sqrt{2}} v\cos\beta & \frac{g_x Q_2}{\sqrt{2}} v\sin\beta & \frac{g_x Q_S}{\sqrt{2}} u \\ 0 & M_W & 0 & m_Z c_W \cos\beta & -m_Z c_W \sin\beta & 0 \\ 0 & 0 & M_Y & -m_Z s_W \cos\beta & m_Z s_W \sin\beta & 0 \\ \frac{g_x Q_1}{\sqrt{2}} v\cos\beta & m_Z c_W \cos\beta & -m_Z s_W \cos\beta & 0 & \lambda u & \lambda v \sin\beta \\ \frac{g_x Q_2}{\sqrt{2}} v\sin\beta & -m_Z c_W \sin\beta & m_Z s_W \sin\beta & \lambda u & 0 & \lambda v\cos\beta \\ \frac{g_x Q_S}{\sqrt{2}} u & 0 & 0 & \lambda v\sin\beta & \lambda v\cos\beta & 0 \end{pmatrix}. \tag{7}$$

Neutralino mass eigenstates $\tilde{\chi}_a^0 (a = 1 \sim 6)$ are related to $\mathcal{N}_j$ by a mixing matrix U as

$$\tilde{\chi}_a^0 = \sum_{j=1}^{6} U_{aj} \mathcal{N}_j, \tag{8}$$

where U is defined in such a way that $U\mathcal{M}U^T$ becomes diagonal.

Here we focus our attention to the composition of the lightest neutralino. If u can take a value similar to $v_{1,2}$ or less than those, the lightest neutralino is expected to be dominated by the singlino $\tilde{S}$ as in the case of the NMSSM and the nMSSM [14,15]. The lightest neutralino with a sizable singlino component can be a good CDM candidate, if it can annihilate sufficiently well [14,15,22]. In the present model, however, the Z' constraints seem to require that u is much larger than $v_{1,2}$ as mentioned before. As the result, $\tilde{\lambda}_x$ and $\tilde{S}$ tend to decouple from the lightest neutralino sector as long as the mass of $\tilde{\lambda}_x$ is assumed to be a similar value to other gaugino mass of $O(m_{1/2})$. The composition of the lightest neutralino is similar to that of the MSSM. Then we cannot find distinctive features in the lightest neutralino sector in this case.

If there exists a large additional contribution to the gaugino mass M_x, for example, following a scenario discussed in the appendix, however, the situation is expected to change drastically. The lightest neutralino can be dominated by the singlino $\tilde{S}$. In fact, if the gaugino $\tilde{\lambda}_x$ is heavy enough to satisfy $M_x \gg \frac{g_x Q_S}{\sqrt{2}} u$, we can integrate out $\tilde{\lambda}_x$ as in case of the seesaw mechanism. A resulting 5×5 neutralino mass matrix can be expressed as

$$\begin{pmatrix} M_W & 0 & m_Z c_W \cos\beta & -m_Z c_W \sin\beta & 0 \\ 0 & M_Y & -m_Z s_W \cos\beta & m_Z s_W \sin\beta & 0 \\ m_Z c_W \cos\beta & -m_Z s_W \cos\beta & -\frac{g_x^2 Q_1^2}{2M_x} v^2 \cos^2\beta & \lambda u & \lambda v \sin\beta \\ -m_Z c_W \sin\beta & m_Z s_W \sin\beta & \lambda u & -\frac{g_x^2 Q_2^2}{2M_x} v^2 \sin^2\beta & \lambda v\cos\beta \\ 0 & 0 & \lambda v \sin\beta & \lambda v \cos\beta & -\frac{g_x^2 Q_S^2}{2M_x} u^2 \end{pmatrix}. \tag{9}$$

This effective mass matrix suggests that the lightest neutralino tends to be dominated by the singlino $\tilde{S}$ as long as $M_{W,Y}$ and $\mu(\equiv \lambda u)$ are not smaller compared with $\frac{g_x^2 Q_S^2 u^2}{2M_x}$. Since M_W and μ cannot to be less than 100 GeV because of the lightest chargino mass bound, this condition is expected to be naturally satisfied in the case of $M_x \gg u$. In such a case, the phenomenology of the lightest neutralino can change largely from that of the MSSM and also the NMSSM. We consider such a situation in the following.

III. SINGLINO-DOMINATED NEUTRALINO DARK MATTER

A. Singlino-dominated lightest neutralino

In the present model, important parameters related to the neutralino sector are the gauge couplings $g_{W,Y}$, g_x, the gaugino mass $M_{W,Y}$, M_x, the extra U(1) charges $Q_{1,2}$, $\tan\beta$, u and the coupling λ, which has the relation to μ. We make several assumptions on these parameters to simplify numerical analyses. Firstly, we impose both the coupling unification and the gaugino mass universality for the MSSM contents. Even if we impose the unification condition for the SM gauge couplings, there remains a freedom for normalization of the extra U(1) coupling constant, which may be defined by $g_x = k g_Y$. In the present analyses we fix it to be $k = 1$. Secondly, we consider the case of $\tan\beta = \sqrt{Q_1/Q_2}$, which automatically guarantees to satisfy the constraint from the ZZ' mixing. For the extra U(1) charge, we assume $Q_1 = -4$ and $Q_2 = -1$. This means $\tan\beta = 2$ and also the singlino can have a rather large charge $Q_S = 5$.[6] Under these assumptions, there remain four free parameters M_W, M_x, u and λ. We practice numerical analyses by varying these parameters.

[6]The extra U(1) charge is normalized with a factor $1/2$ as shown in (5). Under this normalization the charges of $\hat{H}_{1,2}$ used in [16] are $Q_{1,2} = 2$. The extra U(1) charge assignment is constrained by the anomaly free conditions. However, we do not go further into this issue here and we only assume $Q(f_L) = 1$ for the left-handed quarks and leptons as a toy model, for simplicity.

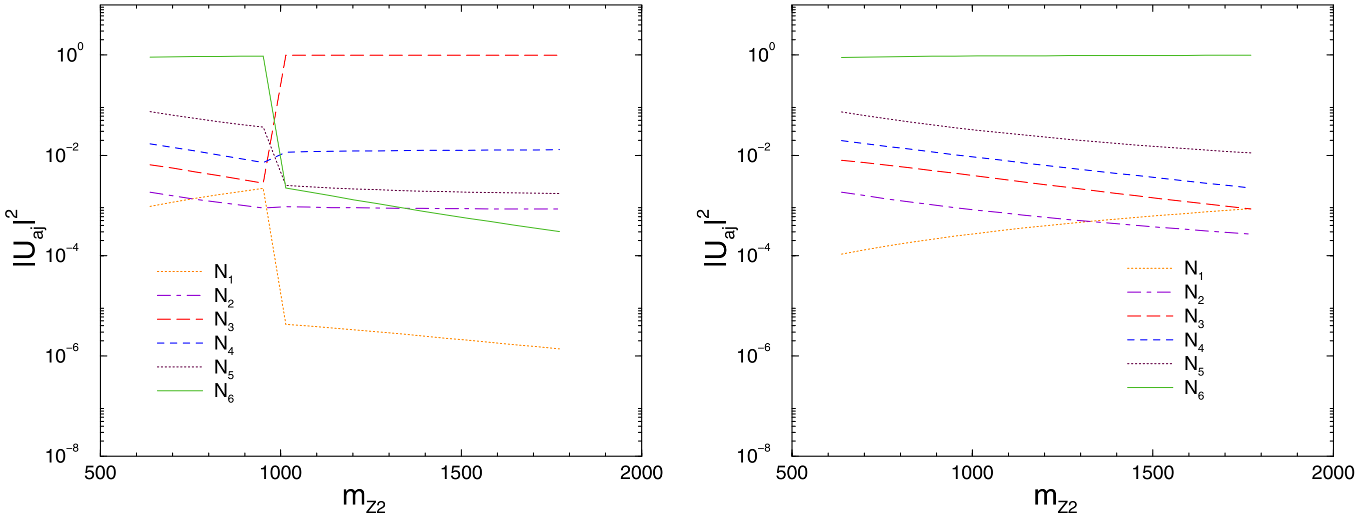

FIG. 1 (color online). The composition $|U_{\ell j}|^2$ of the lightest neutralino $\tilde{\chi}^0_\ell$ in the case of $M_W = \mu = 300$ GeV. M_x is fixed to be 20 TeV and 60 TeV in the left and right panel, respectively. In these panels the Higgs mass bound is not imposed.

We present the results of the numerical analysis obtained by scanning these parameters in the region such as

$$300 \text{ GeV} \le u \le 2300 \text{ GeV}, \qquad 3\text{TeV} \le M_x \le 115 \text{ TeV}, \qquad 0 \le \lambda \equiv \frac{\mu}{u} \le 0.75. \tag{10}$$

The last condition comes from the perturbative bound of the coupling λ [15,23]. Throughout these analyses we impose the constraints on the mass of the chargino [24], the extra gauge boson and the lightest neutral Higgs scalar:

$$m_{\chi^\pm} \ge 104 \text{ GeV}, \qquad m_{Z_2} \ge 600 \text{ GeV}, \qquad m_h \ge 114 \text{ GeV}. \tag{11}$$

Squared mass of sfermions is also checked whether it satisfies the experimental bounds. In this calculation we have to take account of the D-term contribution since it may take a large negative value. Supersymmetry breaking parameters such as the soft scalar mass m_0 and the A parameters are assumed to take a universal value $m_{3/2} = 1$ TeV.

At first we examine the appearance of the singlino-dominated lightest neutralino. In the panels of Fig. 1 we plot the fraction $|U_{\ell j}|^2$ of each component $\mathcal{N}_j$ of the lightest neutralino $\tilde{\chi}^0_\ell$ for the Z' mass m_{Z_2}, which is related to the vacuum expectation value u through Eq. (6).[7] In these panels we choose two typical values of M_x and fix M_W and μ as $M_W = \mu = 300$ GeV. These confirm that the singlino domination of the lightest neutralino can occur even for large values of u which are required by the Z' phenomenology as long as M_x is sufficiently large. The left panel shows that the lightest neutralino rapidly turns from the singlino-dominated one to the bino dominated one when u reaches a certain value. In the right panel the lightest neutralino is dominated by the singlino throughout the whole regions of u since M_x is large enough. In these panels it is interesting that there is an upper bound for m_{Z_2}. This is caused by a condition for the mass of down type squarks since the extra U(1) D-term contributions are negative for them. It should also be noted that a value of μ is fixed in these panels. The coupling λ becomes larger as we make a value of u smaller. This explains such behavior that the Higgsino components $\tilde{H}_{1,2}$ increase in the regions of smaller u. If we make values of M_W and μ larger for relatively small values of M_x, the regions of m_{Z_2} where the lightest neutralino is dominated by the singlino is extended upward, keeping the features shown in the left panel of Fig. 1.

In Fig. 2 we plot the mass eigenvalue of the lightest neutralino for m_{Z_2}. We choose typical values of M_x and also fix both M_W and μ to be 300 GeV and 600 GeV in the left and right panels. We find from these panels that the singlino-dominated lightest neutralino can be very light. The mass becomes smaller than $m_Z/2$ in certain regions of u for sufficiently large values of M_x. Although such a light neutralino seems to be forbidden in the MSSM from both the invisible Z width and the chargino mass bound, the singlino domination makes the model able to evade these constraints. In both panels the small m_{Z_2} regions are found to be forbidden by the conditions imposed on λ and m_{Z_2} in Eqs. (10) and (11). If we remove these conditions, the right panel will show similar behavior as those in the left panel. At the small m_{Z_2} regions in the left panel, the mass eigenvalue increases as m_{Z_2} takes smaller values. Since we fix μ, the coupling λ increases for smaller u values. This makes the Higgsino components of the lightest neutralino in-

[7] m_{Z_2} and u are essentially proportional to each other. In case of $u \gg v_{1,2}$ their proportional constant is given as $m_{Z_2}/u \simeq g_x|Q_S|/\sqrt{2} \simeq 1.26$.

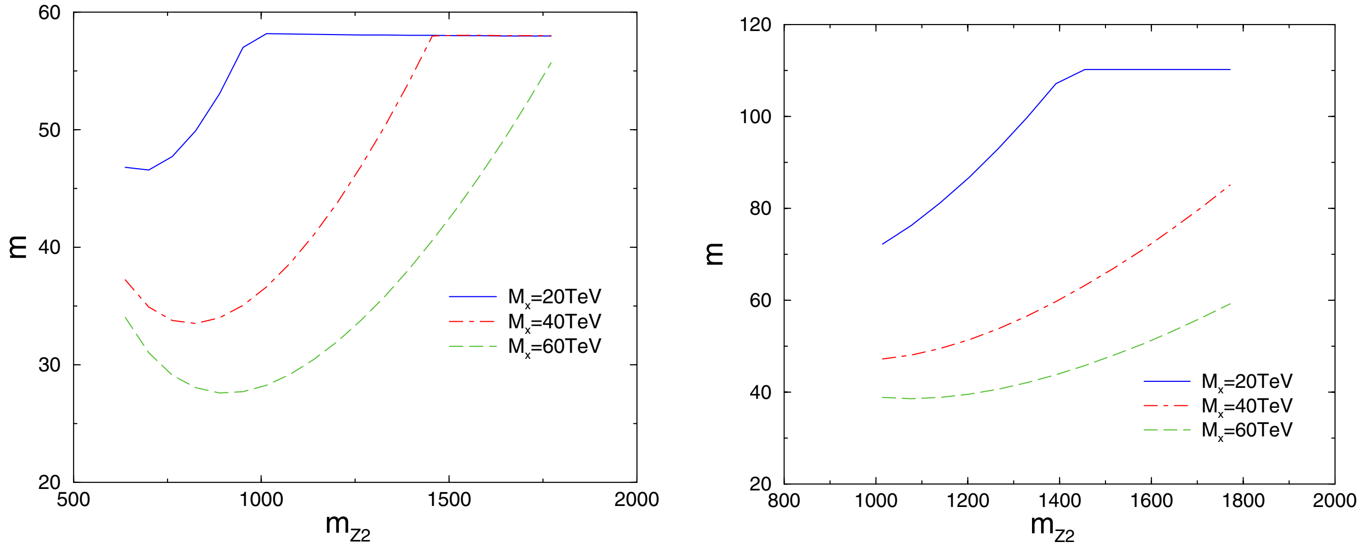

FIG. 2 (color online). The mass eigenvalue $m_{\tilde{\chi}_\ell^0}$ of the lightest neutralino $\tilde{\chi}_\ell^0$. We take $M_W = \mu = 300$ GeV and 600 GeV in the left and right panel, respectively. The Higgs mass bound is not imposed in these panels.

crease in these regions as shown in Fig. 1. These explain the behavior of the mass eigenvalues there. The left panel shows that the mass eigenvalues become constant in the regions where m_{Z_2} is larger than a certain value which is determined by M_x. This behavior can be explained by the fact that the singlino domination finishes there. The lightest neutralino starts being dominated by the bino in larger m_{Z_2} regions. In these regions the lightest neutralino has the similar nature to that in the MSSM. If we make M_W and μ larger, these MSSM like regions start at a larger m_{Z_2} and a corresponding mass eigenvalue also becomes larger as indicated in these panels.

If we regard the singlino-dominated neutralino as the CDM candidate, a very different interaction from the MSSM can contribute to their annihilation cross section. In fact, the lightest neutralino dominated by the singlino $\tilde{S}$ is expected to annihilate mainly through the Z' exchange. However, it is a new channel to be effective only in the case that Z' is not so heavy. Although the lightest neutralino can be lighter than that in the MSSM, if Z' is much heavier than the weak scale, the singlino-dominated lightest neutralino cannot annihilate effectively through this mode and we may have too much relic abundance for it. If we take account of this aspect and also the behavior of the mass eigenvalue shown in Fig. 2, we find that smaller u regions seem to be favored for the explanation of the CDM abundance for a fixed M_x .

We should also remind here that the Higgsino components and the bino component of the lightest neutralino increase for smaller values of m_{Z_2} in the singlino-dominated LSP regions. In these regions the annihilation may also be effectively mediated by the exchange of the Z boson. In fact, as found in Figs. 1 and 2, the lightest neutralino mass $m_{\tilde{\chi}_\ell^0}$ can be $m_Z/2$ there for suitable parameter sets. Thus, the annihilation of the lightest neutralinos can be enhanced due to the Z pole effect in the case that it has substantial Higgsino components. Figures 1 and 2 suggest that such a possibility may be realized more effectively in smaller m_{Z_2} regions for a fixed M_x. It should be noted that this enhancement is expected to occur at the singlino-dominated LSP regions where the lightest neutralino does not start being similar to that of the MSSM and the NMSSM.

It is also useful to note that another difference of this model from the MSSM and the NMSSM exists in the neutral Higgs sector. In this kind of model, the mass of the lightest neutral Higgs scalar has an extra U(1) D-term contribution compared with the NMSSM [10,23]. Since its upper bound can be estimated as

$$m_h^2 \leq m_Z^2\Big[\cos^2 2\beta + \frac{2\lambda^2}{g_W^2 + g_Y^2}\sin^2 2\beta + \frac{g_x^2}{g_W^2 + g_Y^2} \times (Q_1 \cos^2\beta + Q_2 \sin^2\beta)^2\Big] + \Delta m_1^2, \tag{12}$$

it can be heavier than that of the MSSM and also the NMSSM. Due to the second and third terms, even in the regions of the small $\tan\beta$, the lightest neutral Higgs mass m_h can take a large value such as 140 GeV or more, if the one-loop correction Δm_1^2 is taken into account. Since its dominant components of this lightest Higgs scalar are considered to be $H_{1,2}^0$, its interaction with the bino and the Higgsinos is similar to that in the MSSM. Here we remind the behavior of each component $|U_{\ell j}|^2$ shown in Fig. 1 and also the mass eigenvalue $m_{\tilde{\chi}_\ell^0}$ of the lightest neutralino shown in Fig. 2. Then we find that $m_{\tilde{\chi}_\ell^0} \sim m_h/2$ may be easily realized at a certain value of m_{Z_2} if values of M_W, μ and M_x are chosen suitably. The lightest neutralino could have substantial Higgsino components there although the singlino domination is still satisfied. These features suggest that the annihilation of the lightest neutralino mediated by the Higgs exchange may also be enhanced due to the Higgs pole effect. Although small $\tan\beta$ regions are now disfavored by the neutral Higgs mass bound in the MSSM, such regions may still be interesting from a viewpoint of the CDM in the present model.

Finally we comment on the relation to another possibility of the singlino-dominated lightest neutralino. The singlino-dominated lightest neutralino is known to appear in the NMSSM and the S-model [14,15,20]. In these models the lightest neutral Higgs scalar may also be dominated by the singlet scalar since the vacuum expectation value u can take a weak scale or a smaller value. As the result, its mass eigenvalue can be much smaller than the currently known LEP2 lower bound of the neutral Higgs mass. Since u is small, the coupling λ can take a large value. The Higgs exchange process can play a main role for the annihilation of the lightest neutralino in this case. Although the singlino dominates the lightest neutralino also in these models, the phenomenology including the annihilation process of the lightest neutralino is completely different from our models. In our models there may be various possibilities for the mass of the lightest neutralino, which make it possible to consider a different type of annihilation process. If the CDM is found to be the singlino-dominated neutralino, we might be able to refer to its annihilation processes and also the nature of the lightest neutral Higgs scalar to distinguish the present possibility from the NMSSM and the S-model.

B. Relic abundance of the singlino-dominated neutralino

Now we study whether the singlino-dominated neutralino can be the CDM candidate by using numerical analyses of its relic abundance. At first, we briefly review how to estimate the relic abundance of thermal plasma in the expanding universe [4,5]. The relic abundance of the thermal stable lightest neutralino $\tilde{\chi}_\ell^0$ can be evaluated as the thermal abundance at its freeze-out temperature T_F, which can be determined by $H(T_F) \sim \Gamma_{\tilde{\chi}_\ell^0}$. $H(T_F)$ is the Hubble parameter at T_F. $\Gamma_{\tilde{\chi}_\ell^0}$ is an annihilation rate of $\tilde{\chi}_\ell^0$ and it can be written as $\Gamma_{\tilde{\chi}_\ell^0} = \langle \sigma_{\rm ann} v \rangle n_{\tilde{\chi}_\ell^0}$, where $\langle \sigma_{\rm ann} v \rangle$ is thermal average of the product of the annihilation cross section $\sigma_{\rm ann}$ and the relative velocity v of annihilating $\tilde{\chi}_\ell^0$s in the center of mass frame. Thermal number density of nonrelativistic $\tilde{\chi}_\ell^0$s at this temperature is expressed by $n_{\tilde{\chi}_\ell^0}$. If we introduce a dimensionless parameter $x_F = m_{\tilde{\chi}_\ell^0}/T_F$, we find that x_F can be represented as

$$x_F = \ln \frac{m_{\rm pl} m_{\tilde{\chi}_\ell^0} \langle \sigma_{\rm ann} v \rangle}{13 (g_* x_F^{-1})^{1/2}}, \tag{13}$$

where g_* enumerates the degrees of freedom of relativistic particles at T_F. Using this x_F, the present abundance of $\tilde{\chi}_\ell^0$ can be estimated as

$$\Omega_\chi h^2|_0 = \frac{m_{\tilde{\chi}_\ell^0} n_{\tilde{\chi}_\ell^0}}{\rho_{\rm cr}/h^2} \bigg|_0 \simeq \frac{7.3 \times 10^{-11} g_*^{-1/2} x_F}{\langle \sigma_{\rm ann} v \rangle \ {\rm GeV}^3}. \tag{14}$$

Here we may use the approximation such as

$$\langle \sigma_{\rm ann} v \rangle \simeq a + (b - 3a/2)/x_F \tag{15}$$

under the nonrelativistic expansion $\sigma_{\rm ann} v \simeq a + b v^2/6$. Detailed formulas of a and b for annihilation processes induced by the exchange of various fields can be found in [5,6].

If the lightest neutralino $\tilde{\chi}_\ell^0$ is lighter than m_Z, only the annihilation into the SM fermion-antifermion pairs $\tilde{\chi}_\ell^0 \tilde{\chi}_\ell^0 \to f \bar{f}$ is expected to occur. We consider this case. The neutralino annihilation processes in the models with an extra U(1) are expected to be mediated by the exchange of Z, Z' and the neutral Higgs scalars in the s-channel and by the sfermion exchange in the t-channel as usual. However, since the singlino dominates the lightest neutralino in our case, its annihilation cross section is expected to have a dominant contribution from the Z' exchange. If we define contribution of this process to a and b in Eq. (15) as a_f and b_f, they can be expressed as [16]

$$\begin{aligned} a_f &= \frac{2c_f}{\pi} \frac{g_x^4 m_f^2}{m_{Z_2}^4} \sqrt{1 - \frac{m_f^2}{m_{\tilde{\chi}_\ell^0}^2}} \bigg[\left(\frac{Q(f_L)}{2} - \frac{Q(f_R)}{2} \right)^2 \\ &\quad \times \left(\sum_j \frac{Q_j}{2} U_{\ell j}^2 \right)^2 \bigg], \\ b_f &= \left(-\frac{9}{2} + \frac{3}{4} \frac{m_f^2}{m_{\tilde{\chi}_\ell^0}^2 - m_f^2} \right) a_f + \frac{2c_f}{\pi} \left(\frac{g_x^2 m_{\tilde{\chi}_\ell^0} \sum_j (Q_j/2) U_{\ell j}^2}{4 m_{\tilde{\chi}_\ell^0}^2 - m_{Z_2}^2} \right)^2 \\ &\quad \times \sqrt{1 - \frac{m_f^2}{m_{\tilde{\chi}_\ell^0}^2}} \bigg[\left(\frac{Q(f_L)}{2} \right)^2 + \left(\frac{Q(f_R)}{2} \right)^2 \bigg] \left(4 + \frac{2 m_f^2}{m_{\tilde{\chi}_\ell^0}^2} \right), \end{aligned} \tag{16}$$

where $c_f = 1$ for leptons and 3 for quarks. $m_{\tilde{\chi}_\ell^0}$ stands for the mass of the singlino-dominated lightest neutralino $\tilde{\chi}_\ell^0$. The extra U(1) charges of fermions $f_{L,R}$ are denoted by $Q(f_L)$ and $Q(f_R)$. If we note the charge conservation in Yukawa couplings, we find that only $Q_{1,2}$ and $Q(f_L)$ are necessary to fix the relevant charges. For other annihilation processes mediated by the MSSM contents, we can find the cross section formulas in [5,6]. In the numerical calculation we also take account of these.

We now show that this singlino-dominated neutralino can have suitable relic abundance as dark matter. In Fig. 3 we show seven regions in the (m_{Z_2}, M_x) plane by surrounding them with various kinds of lines, where the singlino-

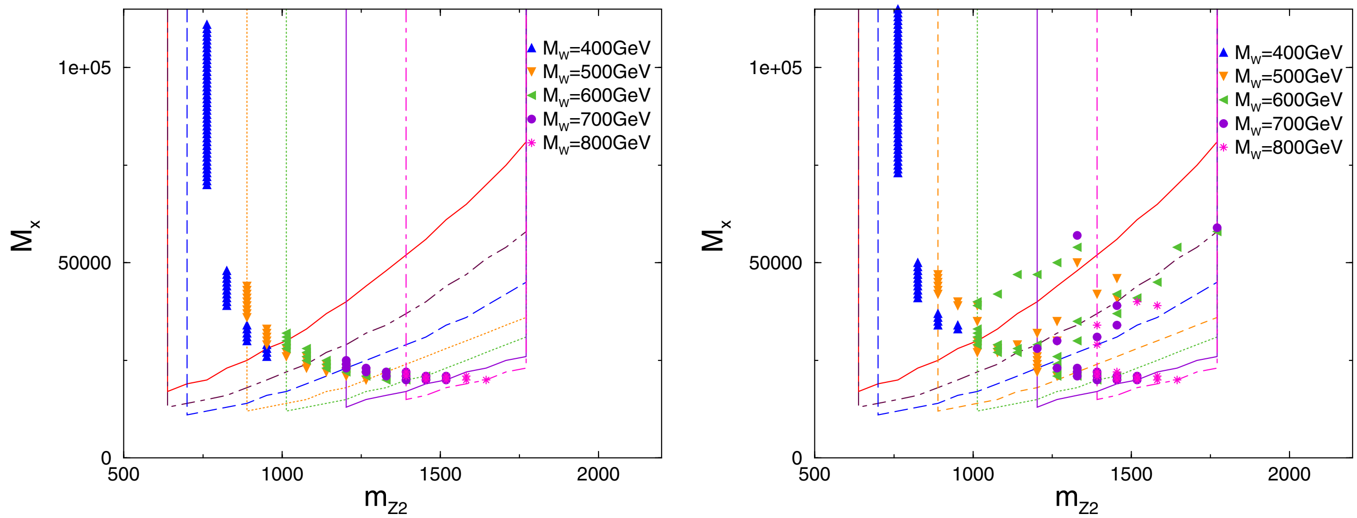

FIG. 3 (color online). The regions in the (m_{Z2}, M_x) plane where the singlino-dominated lightest neutralino is realized. Points which satisfy the CDM constraints from the WMAP are plotted for various values of $M_W = \mu$. Only the Z' exchange is taken into account in the left panel. In the right panel all processes in the MSSM are also included.

dominated lightest neutralino is realized for fixed values of $M_W = \mu$ within the parameter space defined by (10) under the conditions (11). The value of M_W is taken from 200 GeV to 800 GeV at a 100 GeV interval. The regions corresponding to each value of M_W are plotted by a solid line (200 GeV), a dash-dotted line (300 GeV), a dashed line (400 GeV), a dotted line (500 GeV) etc., respectively. The vertical lines corresponding to 200 GeV and 300 GeV overlap at ~640 GeV. The regions appearing for a larger m_{Z_2} correspond to the one for a larger M_W. In each region, the lower bound of m_{Z_2} is determined by the condition for λ given in (10) except for the case of $M_W = 200$ GeV, for which it comes from the m_{Z_2} bound. In all regions the upper bound of m_{Z_2} takes a common value which comes from the down type squark mass condition as mentioned before. The lower bound of M_x for each value of m_{Z_2} comes from the requirement that the lightest neutralino is dominated by the singlino.

In the left panel of Fig. 3 we also plot points where the $\Omega_{\rm CDM}$ constraint from the WMAP is satisfied for various values of $M_W = \mu$. In this panel we only take account of the Z' exchange process described by Eq. (16). These points are found by scanning u and M_x at the interval of 50 GeV and 1000 GeV, respectively. These solutions are obtained for $x_F \simeq 22 - 23$. The $\Omega_{\rm CDM}$ solutions for $M_W = 200$ GeV and 300 GeV are excluded by the condition for the Higgs mass $m_h \geq 114$ GeV. This panel shows that each point satisfying the WMAP constraint is found only in the singlino-dominated LSP regions. This seems consistent with the discussion given in the previous part.

In the right panel we plot points where the $\Omega_{\rm CDM}$ constraint from the WMAP is satisfied by including all the annihilation processes in the MSSM such as the Z boson exchange, the Higgs scalar exchange and so on.[8] These solutions are obtained for $x_F \simeq 22 - 23$. For these solutions both the mass of the lightest neutralino $m_{\tilde{\chi}_\ell^0}$ and the lightest Higgs m_h are shown in Table I. The Higgs mass decreases for larger values of u. This is expected from Eq. (12), since the second term in the brackets of the right-hand side of Eq. (12) decreases as increasing u for a fixed μ. This feature forbids the solutions in larger u regions in the case of smaller values of M_W. Table I shows that there are possibilities such that $m_{\tilde{\chi}_\ell^0}$ takes values near $m_Z/2$ or $m_h/2$ in the case of $M_W \geq 500$ GeV. Corresponding to these, we can find that additional solutions appear in this panel compared with the left panel. These solutions may be understood along the line discussed already. They are considered to appear as the result of the additional effect caused by the enhancement of the annihilation due to the Z pole or the lightest neutral Higgs pole. Also in this panel, we find that all solutions appear only in the regions which satisfy the singlino domination condition. We can also find these qualitative features for other parameter sets.

From these figures we find that the singlino-dominated lightest neutralino can be a good CDM candidate. Its annihilation can be mediated by various processes. This

TABLE I. $m_{\tilde{\chi}_\ell^0}$ and m_h, which give the solutions in the right panel of Fig. 3 for the CDM constraints from the WMAP. The mass unit is GeV.

M_W	400	500	600	700	800
$m_{\tilde{\chi}_\ell^0}$	31–44	40–87	45–96	45–120	70–144
m_h	116–129	115–146	117–154	127–154	142–153

[8]In this calculation, as an example, we take $\sqrt{\Delta m_1^2}$ as 80 GeV. Even if we change this value, qualitatively similar results can be obtained.

is considered to be caused by the feature in the present model that the singlino-dominated lightest neutralino can have its mass eigenvalue in a rather wide range.

In the above study we impose $m_{Z_2} \geq 600$ GeV on the Z' mass for simplicity, although this bound depends on the models. We need to confirm that our solutions are consistent with the result of the direct search of Z' at the Tevatron. The CDF limit at $\sqrt{s} = 1.8$ TeV is expressed as [25]

$$\sigma(p\bar{p} \to Z'X)B(Z' \to e^+e^-, \mu^+\mu^-) < 0.04 \text{ pb.} \quad (17)$$

We calculated this σB for the dilepton modes for each solution shown in the right panel of Fig. 3. Then we found that all solutions satisfied this CDF bound. In the present model Z' can have a rather large branching ratio such as 15–19% into the neutralino sector.

We comment on a desired feature for models in order for the present scenario to work well finally. As mentioned already, the strength of the extra U(1) interaction is an important factor for the annihilation of the singlino-dominated neutralino caused by the s-channel exchange of Z'. It is related to the normalization constant k or the extra U(1) charge of various fields. Since $k = O(1)$ is naturally expected, the charge $|Q_S|$ of the singlet chiral superfield $\hat{S}$ should be larger compared with those of other fields. If we assume to satisfy $\tan\beta \simeq \sqrt{Q_1/Q_2}$ so as to evade the constraint from the ZZ' mixing independently of the Z' mass, the charge conservation automatically makes $|Q_S|$ larger than the charges $|Q_{1,2}|$ of the Higgs doublets $H_{1,2}$. Thus, as stressed before, the annihilation of the singlino-dominated lightest neutralinos is expected to be enhanced as its singlino component increases. If these features are satisfied, the present scenario seems to favor a small $\tan\beta$ generally.

A large value of $|Q_S|$ makes the coupling of the singlino-dominated lightest neutralino with Z' larger. This means that the branching ratio of the Z' decay may also be dominated by the decay modes into the singlino-dominated neutralinos. If this happens, the current mass bound of Z' may be relaxed and allowed parameter regions can be extended. Although these aspects are strongly dependent on models, it seems worthy of proceeding with the detailed studies in more realistic cases derived from the E_6 model and examining the possibility to find Z' at the LHC. It may also be interesting to study whether we can construct this kind of models on the basis of a fundamental framework like string theory.

IV. SUMMARY

We studied a possibility that the singlino dominates the lightest neutralino in the supersymmetric models with an extra U(1), which give an elegant weak scale solution for the μ problem. For that purpose we assumed a supersymmetry breaking scenario which induces nonuniversal mass for the extra U(1) gaugino. When the extra U(1) gaugino is very heavy as compared with the other gauginos, whose mass is kept in the ordinary range, the lightest neutralino can be shown to be dominated by the singlino even if the vacuum expectation value u of the singlet scalar field is large enough to permit the extra U(1) gauge field Z' to satisfy the experimental constraints. This possibility is very different from what happens in the usual models with an extra U(1), where the lightest neutralino is expected to have the similar nature to that of the MSSM because of the large u. In the NMSSM and a special type of models with an extra U(1), the singlino-dominated lightest neutralino is known to appear in the case of a small vacuum expectation value u unless the coupling λ is very small. However, our model can realize the singlino-dominated neutralino in a very different manner from those.

We also studied whether this singlino-dominated lightest neutralino can have the suitable relic density as the CDM candidate based on the WMAP results. We found that it can be a nice CDM candidate in non-negligible parameter regions as long as the model satisfies $\tan\beta \simeq \sqrt{Q_1/Q_2}$, which comes from the ZZ' mixing constraint. This CDM candidate has very different nature from that in the MSSM and the NMSSM. The model might be distinguished through the studies of phenomena related to the neutralino and the neutral Higgs scalar. Detailed studies of these aspects seem very interesting. We will present such studies in a different publication.

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APPENDIX

In usual supersymmetry breaking scenarios, gaugino mass is universal. If we consider much larger gaugino mass compared with the weak scale in a universal gaugino mass framework, the mass of the gluinos and the winos also becomes large to defeat the SM gauge coupling unification, for example. The gaugino mass universality also imposes severe constraints on phenomenological features of the model. If we assume the universality of the gaugino mass and also the coupling unification, the mass of the gauginos in the MSSM satisfies the unification relation such as $M_g/g_s^2 = M_W/g_W^2 = 5M_Y/3g_Y^2$. Since the current lower bound of the chargino mass is shown to be 104 GeV [24], M_W is difficult to be smaller than 100 GeV. This fact together with the unification relation constrains the allowed regions of M_Y. Thus, the lightest neutralino cannot be so light under these requirements in the MSSM. In the models with an extra U(1) which are not a type of the S-model, the situation is similar to this as long as the gaugino mass is assumed to be universal.

A few examples which can realize nonuniversal gaugino mass have been proposed by now.[9] In those cases, however, nonuniversality is not so large that it seems to be difficult to make the lightest neutralino be dominated by the singlino unlike the models assumed in the text. Here we propose a new scenario which makes an Abelian gaugino mass largely different from others and then the singlino-dominated neutralino the lightest one.

It is known that kinetic term mixing can generally appear among the Abelian gauge fields in multi U(1)s models [30–32]. In the following, such mixing is assumed to exist between two Abelian gauge fields, each of which belongs to the hidden and observable sector. In that case we show that there can be an additional contribution to the corresponding Abelian gaugino mass in the observable sector, if we make some assumptions on the superpotential and also the supersymmetry breaking in the hidden sector. This additional contribution may make the Abelian gaugino mass different from others in the observable sector.

For simplicity, we consider a supersymmetric $U(1)_a \times U(1)_b$ model where $U(1)_a$ and $U(1)_b$ belong to the hidden sector and the observable sector, respectively. We suppose that $\hat{W}^\alpha_{a,b}$ is a chiral superfield with a spinor index α, which contains a field strength of $U(1)_{a,b}$. Since $\hat{W}^\alpha_{a,b}$ is gauge invariant, gauge invariant kinetic terms can be expressed as

$$\mathcal{L}_{\rm kin} = \int d^2\theta\left(\frac{1}{32}\hat{W}^\alpha_a\hat{W}_{a\alpha} + \frac{1}{32}\hat{W}^\alpha_b\hat{W}_{b\alpha} + \frac{\sin\chi}{16}\hat{W}^\alpha_a\hat{W}_{b\alpha}\right), \tag{A1}$$

where it should be reminded that a mixing term is generally allowed at least from a viewpoint of symmetry. Although some origins such as string one-loop effects may be considered for this mixing term [31], we do not go further into this issue here but we only treat $\sin\chi$ in Eq. (A1) as a free parameter.

This mixing can be resolved by practicing the transformation [19,30]

$$\begin{pmatrix}\hat{W}^\alpha_a\\ \hat{W}^\alpha_b\end{pmatrix} = \begin{pmatrix}1 & -\tan\chi\\ 0 & 1/\cos\chi\end{pmatrix}\begin{pmatrix}\hat{W}^\alpha_h\\ \hat{W}^\alpha_x\end{pmatrix}. \tag{A2}$$

If we use a new basis $(\hat{W}^\alpha_h, \hat{W}^\alpha_x)$, the covariant derivative in the observable sector can be written as

$$D^\mu = \partial^\mu + i\left(-g_aQ_a\tan\chi + \frac{g_bQ_b}{\cos\chi}\right)A^\mu_x. \tag{A3}$$

This shows that the gauge field A^μ_x in the observable sector can interact with the fields having a nonzero charge Q_a in the hidden sector. However, since such fields are generally considered to be heavy enough and $\sin\chi$ is expected to be small, we can safely expect that there is no phenomenological contradiction at the present stage.

Here we consider that the Abelian gauginos in both sectors obtain mass through the supersymmetry breaking in the hidden sector such as

$$\mathcal{L}^m_{\rm gaugino} = m_a\tilde{\lambda}_a\tilde{\lambda}_a + m_b\tilde{\lambda}_b\tilde{\lambda}_b, \tag{A4}$$

where the mass m_b of the gaugino in the observable sector may be considered as the ordinary universal mass $m_{1/2}$. If we can assume that $m_a \gg m_b$ is satisfied, these mass terms are rewritten by using the new basis (A2) as follows,

$$\tilde{\mathcal{L}}^m_{\rm gaugino} = m_a\tilde{\lambda}_h\tilde{\lambda}_h + (m_b + m_a\sin^2\chi)\tilde{\lambda}_x\tilde{\lambda}_x, \tag{A5}$$

where we also use $\sin\chi \ll 1$ in this derivation. This suggests that the Abelian gaugino mass in the observable sector can have an additional contribution due to the Abelian gauge kinetic term mixing with the gaugino in the hidden sector. This new contribution can be a dominant one when the supersymmetry breaking in the hidden sector satisfies $m_a\sin^2\chi > m_b$. In this case the universality of the mass of gauginos in the observable sector can be violated in the Abelian part.

We present an example for the supersymmetry breaking scenario which can satisfy the above mentioned condition in a framework of the gravity mediation supersymmetry breaking. We consider a hidden sector which contains the chiral superfields $\hat{\Phi}_{1,2}$ having a nonzero charge of $U(1)_a$. It is also supposed that the model contains various neutral chiral superfields like a modulus, which are represented by $\hat{M}$ together. They are defined as dimensionless fields. Matter superfields in the observable sector are denoted by $\hat{\Psi}_I$. The Kähler potential and the superpotential relevant to the present argument are supposed to be written as[10]

$$\mathcal{K} = \kappa^{-2}\hat{K}(\hat{M}) + \hat{\Phi}^*_1\hat{\Phi}_1 + \hat{\Phi}^*_2\hat{\Phi}_2 + \hat{\Psi}^*_I\hat{\Psi}_I + \ldots,$$
$$\mathcal{W} = \hat{W}_0(\hat{M}) + \hat{W}_1(\hat{M})\hat{\Phi}_1\hat{\Phi}_2 + \hat{Y}_{IJK}(\hat{M})\hat{\Psi}_I\hat{\Psi}_J\hat{\Psi}_K + \ldots, \tag{A6}$$

where κ^{-1} is the reduced Planck mass and $Q_a(\hat{\Phi}_1) + Q_a(\hat{\Phi}_2) = 0$ is assumed. As a source relevant to the supersymmetry breaking in the hidden sector, we adopt a usual assumption in the case of the gravity mediation supersymmetry breaking. That is, the supersymmetry breaking effect is assumed to be parametrized by [33]

$$F_M \equiv \kappa^2 e^{K/2}(W_0\partial_M K + \partial_M W_0), \tag{A7}$$

which is supposed to be $O(m_{3/2})$ as long as the vacuum

[9]The mass of the gauginos is known to be nonuniversal in some kinds of models, for example, in the multimoduli supersymmetry breaking [26], the intersecting D-brane models [27] and a certain type of gauge mediation model [28]. Phenomenological effects of the nonuniversal gaugino mass on the neutralino sector is also studied in [29] in a different context from ours.

[10]For simplicity, we assume minimal kinetic terms for the matter fields.

energy is assumed to vanish. The gravitino mass $m_{3/2}$ is defined by $m_{3/2} \equiv \kappa^2 e^{K/2} W_0$.

Applying this assumption to the scalar potential formula in the supergravity, we can have well known soft supersymmetry breaking terms of $O(m_{3/2})$ in the observable sector [33]. The gaugino mass is generated as [34]

$$m_{1/2} = \frac{1}{2Re[f_A(M)]} F^M \partial_M f_A(M), \qquad \text{(A8)}$$

where $f_A(M)$ is a gauge kinetic function for the gauge factor group G_A. If $f_A(M)$ takes the same form for each factor group, universal gaugino mass is generated and takes a value of $O(m_{3/2})$. This is the ordinary scenario. In the present case, the gaugino mass m_b in Eq. (A4) is also expected to be induced by this gravity mediation and take the universal value $m_{1/2}$.

On the other hand, the gaugino mass m_a in the hidden sector is generated by the mediation of the charged chiral superfields $\hat{\Phi}_{1,2}$ due to the second term in $\mathcal{W}$ as in the gauge mediation supersymmetry breaking scenario [35]. Since it can be generated by one-loop diagrams which have the component fields of $\hat{\Phi}_{1,2}$ in internal lines, it is approximately expressed as

$$m_a = \frac{g_a^2}{16\pi^2} \frac{\langle F_1 \rangle}{\langle S_1 \rangle}, \qquad \text{(A9)}$$

where we define that S_1 and F_1 are the scalar and auxiliary component of $\hat{W}_1$, respectively. Since we are considering the gravity mediation supersymmetry breaking, a supersymmetry breaking scale in the hidden sector should be large as expected from Eq. (A7). It may be natural to assume that $\langle F_1 \rangle = O(\kappa^{-1} m_{3/2})$ and $\langle S_1 \rangle = O((\kappa^{-1} m_{3/2})^{1/2})$. If we use these values in Eq. (A9), we find that the gaugino $\tilde{\lambda}_h$ in the hidden sector obtains the mass

$$m_a = \frac{g_a^2}{16\pi^2} O((\kappa^{-1} m_{3/2})^{1/2}). \qquad \text{(A10)}$$

Since this m_a can be much larger than the ordinary gravity mediated contribution m_b, the additional contribution $m_a \sin^2\chi$ to the Abelian gaugino mass in Eq. (A5) can break the gaugino mass universality in the observable sector. In fact, since $\sin\chi$ has a suitable value such as $\chi = O(10^{-1})$,[11] we can expect that $m_a \sin^2\chi > m_b$ is realized and the Abelian gaugino mass characterized by $m_a \sin^2\chi$ can take a much larger value than other universal ones $O(m_{1/2})$.[12]

[11] The string one-loop effects may bring this order of mixing as discussed in [31].

[12] We should note that an opposite case might also be possible. In fact, if the absolute values of m_b and $m_a \sin^2\chi$ are the same order, two contributions may substantially cancel each other to realize much smaller value than $m_{1/2}$.

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