Split-SUSY dark matter in light of direct detection limits

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Abstract

We examine the present and future XENON limits on the neutralino dark matter in split supersymmetry (split-SUSY). Through a scan over the parameter space under the current constraints from collider experiments and the WMAP measurement of the dark matter relic density, we find that in the allowed parameter space a large part has been excluded by the present XENON100 limits and a further largish part can be covered by the future exposure (6000 kg-day). In case of unobservation of dark matter with such an exposure in the future, the lightest neutralino will remain bino-like and its annihilation is mainly through exchanging the SM-like Higgs boson in order to get the required relic density.

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So far the only phenomenology crisis which requires new physics at the TeV scale seems to be the cosmic dark matter. Unlike neutrino oscillations which may indicate some new physics at a very high unaccessible energy scale, the cosmic dark matter naturally points to a WIMP (weakly interacting massive particle) which should appear in some new physics around TeV scale. A perfect candidate for such a WIMP is the lightest neutralino in low energy supersymmetry (SUSY). As a specific low energy SUSY model, the split-SUSY \cite{1} is phenomenologically attractive because it just gives up the acesitic (fine-tuning) problem while maintains the phenomenologically required dark matter and the gauge coupling unification. This model also gets rid of the notorious supersymmetric flavor problem because of the assumed superheavy sfermions. Actually, in this framework no scalar particles except the SM-like Higgs boson are accessible at the foreseeable particle colliders. So the only way to explore this model is to study its gaugino/higgsino sector, for which the dark matter detection experiments like XENON \cite{2} and CDMS \cite{3} can interplay with the collider experiments to allow for a comprehensive test.

Recently, the CDMS and XENON collaborations reported their null search results which set rather stringent limits on the dark matter scattering cross section \cite{2,3}. The implications of these new limits for the neutralino dark matter in low energy SUSY models have been discussed recently (see, e.g., \cite{4–6}). On the other hand, the CoGeNT \cite{7} and DAMA/LIBRA \cite{8} collaborations reported some excesses which are consistent with an explanation of a light dark matter with a mass around 10 GeV (albeit not corroborated by CDMS or XENON results). The possible existence of such a light dark matter also stimulated some theoretical studies in low energy SUSY models \cite{9}.

In this note we discuss the implication of the direct detection limits for the neutralino dark matter in split-SUSY. Since the most stringent limits come from the XENON100 results, we will focus on the present and future (6000 kg-day) limits from XENON. We will perform a scan over the parameter space under the current constraints from collider experiments and the WMAP measurement of the dark matter relic density, and display the allowed parameter space in the plane of the dark matter scattering rate versus the dark matter mass. Then we can see how large a parameter space can be excluded by the present and future XENON limits. Further, we will show the implication of XENON limits on the properties of the
neutralino dark matter and the lightest chargino.

We start our analysis by writing out the chargino mass matrix:

\[
\mathcal{M}_{\chi^\pm} = \begin{pmatrix} M_2 & \sqrt{2}m_W \sin \beta \\ \sqrt{2}m_W \cos \beta & \mu \end{pmatrix},
\]

(1)

where the 2-components spinors are defined as \( \tilde{\psi}^+ = (-i\tilde{\omega}^+ + \tilde{h}_2^+)^T \), \( \tilde{\psi}^- = (-i\tilde{\omega}^- + \tilde{h}_1^-)^T \). The neutralino mass matrix is given by

\[
\mathcal{M}_{\chi^0} = \begin{pmatrix} M_1 & 0 & -m_Z \sin \theta_W \cos \beta & m_Z \sin \theta_W \sin \beta \\ 0 & M_2 & m_Z \cos \theta_W \cos \beta & -m_Z \cos \theta_W \sin \beta \\ -m_Z \sin \theta_W \cos \beta & m_Z \cos \theta_W \cos \beta & 0 & -\mu \\ m_Z \sin \theta_W \sin \beta & -m_Z \cos \theta_W \sin \beta & -\mu & 0 \end{pmatrix},
\]

(2)

where the 2-component spinors are defined as \( \tilde{\psi}^0 = (-i\tilde{b}, -i\tilde{\omega}_3, \tilde{h}_1, \tilde{h}_2)^T \). In the above mass matrices, \( M_1 \) and \( M_2 \) are respectively the \( U(1) \) and \( SU(2) \) gaugino mass parameters, \( \mu \) is the mass parameter in the mixing term \( -\mu \epsilon_{ij} H_i^1 H_j^2 \) in the superpotential, and \( \tan \beta \equiv v_2/v_1 \) is ratio of the vacuum expectation values of the two Higgs doublets.

The chargino mass matrix (1) is diagonalized by \( U^* \mathcal{M}_{\chi^\pm} V^\dagger \) to give two chargino mass eigenstates \( \chi^+_{1,2} \) with the convention \( M_{\chi^+_1} < M_{\chi^+_2} \). The eigenstates may be wino \((-i\tilde{\omega}^+)\) dominant or higgsino \((\tilde{h}_i^+)\) dominant. Similarly, the neutralino mass matrix (2) is diagonalized by \( N^* \mathcal{M}_{\chi^0} N^\dagger \) to give four neutralino mass eigenstates \( \chi^0_{1,2,3,4} \) with the convention \( M_{\chi^0_1} < M_{\chi^0_2} < M_{\chi^0_3} < M_{\chi^0_4} \). The neutralinos may be bino \((-i\tilde{b})\), wino\((-i\tilde{\omega}_3)\) or higgsino \((\tilde{h}_i)\) dominant. So the masses and mixings of charginos and neutralinos are determined by four parameters: \( M_1, M_2, \mu \) and \( \tan \beta \).

The spin-independent (SI) interaction between the lightest neutralino \( \chi^0_1 \) and the nucleon (denoted by \( f_p \) for proton and \( f_n \) for neutron) is induced by exchanging the SM-like Higgs boson or the squarks at tree level \([10, 11]\). In split-SUSY, the squark contribution is negligibly small, so \( f_p \) is approximated by \([10]\) (similarly for \( f_n \))

\[
f_p \approx \sum_{q=u,d,s} \frac{f_H^q}{m_q} m_p f_{T_q}^{(p)} + \frac{2}{27} f_{T_G} \sum_{q=c,b,t} \frac{f_H^q}{m_q} m_p,
\]

(3)

where \( f_{T_q}^{(p)} \) denotes the fraction of \( m_p \) (proton mass) from a light quark \( q \) while \( f_{T_G} = 1 - \sum_{u,d,s} f_{T_q}^{(p)} \) is the heavy quark contribution through gluon exchange. \( f_H^q \) is the coefficient
of the effective scalar operator given by \[10\]
\[ f^H_q = m_q \frac{g^2_2}{4m_W} C_{h\tilde{\chi}\tilde{\chi}} C_{hqq}, \]
with \(C\) standing for the corresponding Yukawa couplings. The \(\tilde{\chi}^0\)-nucleus scattering rate is then given by \[10\]
\[ \sigma^{SI} = \frac{4}{\pi} \left( \frac{m_{\tilde{\chi}^0} m_T}{m_{\tilde{\chi}^0} + m_T} \right)^2 \times \left( n_p f_p + n_n f_n \right)^2, \]
where \(m_T\) is the mass of target nucleus and \(n_p(n_n)\) is the number of proton (neutron) in the target nucleus.

From the above formulas we can infer in which situation the scattering cross section is large. Eq.\([4]\) indicates that this occurs when \(C_{h\tilde{\chi}\tilde{\chi}}\) and/or \(C_{hqq}\) get enhanced. As the Higgs boson is SM-like, \(C_{hqq}\) has no \(\tan \beta\) enhancement for the down-type quark. We here only check the behavior of \(C_{h\tilde{\chi}\tilde{\chi}}\) with the variation of the relevant SUSY parameters. For a bino-like \(\tilde{\chi}^0_1\), this coupling is generated through the bino-higgsino mixing and thus a large \(C_{h\tilde{\chi}\tilde{\chi}}\) needs a large mixing, which means a small \(\mu\). To make this statement clearer, we consider the limit \(M_1 \ll M_2, \mu\) (\(M_1, M_2\) and \(\mu\) denoting respectively the mass of bino, wino and higgsino). After diagonalizing the neutralino mass matrix in a perturbative way, one can get \[4\]
\[ C_{h\tilde{\chi}\tilde{\chi}} \simeq \frac{m_Z \sin \theta_W \tan \theta_W}{M_1^2 - \mu^2} [M_1 + \mu \sin 2\beta]. \]

So the coupling \(C_{h\tilde{\chi}\tilde{\chi}}\) becomes large when \(\mu\) approaches downward to \(M_1\).

In our numerical calculation for the dark matter-nucleon scattering rate, we considered all the contributions (including QCD corrections) known so far. We take \(f^{(p)}_{T_u} = 0.023, f^{(p)}_{T_d} = 0.032, f^{(n)}_{T_u} = 0.017, f^{(n)}_{T_d} = 0.041\) and \(f^{(p)}_{T_s} = f^{(n)}_{T_s} = 0.020\) \[12-14\]. Note that here the value of \(f_{T_s}\) is much smaller than that taken in most previous studies. This small value comes from the recent lattice simulation \[15\], and it can reduce the scattering rate significantly.

For the calculation of the SM-like Higgs boson mass, since in split-SUSY we have \(\log(m_f^2/m_t^2) \gg 1\) which will spoil the convergence of the traditional loop expansion in evaluating the SUSY effects on the Higgs boson self-energy, so we use the effective potential method which involves the renormalization group evolution of the SUSY effects from the squark scale to the electroweak scale \[16\]. This computation method is employed in the package NMSSMTools \[17\]. This package, which primarily acts as an important tool for
the study of the phenomenology of the Next-to-Minimal Supersymmetric Model, can also be applied to the MSSM case by setting $\lambda = \kappa$ approach zero (with this setting the singlet superfield decouples from the rest of the theory so that the MSSM phenomenology is recovered \cite{18}). Throughout our calculations we use this package.

As shown in \cite{19}, the effects of the sfermion and the heavy Higgs bosons on electroweak theory begin to decouple when the particles are heavier than several TeV. So in our analysis we set $m_{\tilde{f}} = m_A \equiv M_0 = 10$ TeV and the trilinear term $A_t = A_b = 0$ TeV to simulate the split-SUSY scenario. We checked that the results with $M_0 = 100$ TeV are quite similar to the results with $M_0 = 10$ TeV. We also checked that the package DarkSUSY \cite{20}, which calculates the Higgs mass by loop expansion, can yield similar results if we set $M_0 = 10$ TeV, but it does not work if we choose $M_0 = 100$ TeV.

The remained SUSY parameters are $\tan \beta$, $M_1$, $M_2$, $M_3$, $\mu$. We assume the SUSY GUT relation for the gaugino masses, i.e. $M_1 = (5s_W^2/3(1 - s_W^2))M_2 \simeq 0.5M_2$ and $M_3 = (\alpha_s s_W^2/\alpha_{EW})M_2 \simeq 3M_2$ at the electroweak scale, and thus we only have three parameters to explore. In our analysis, we scan these parameter in the ranges

$$1 < \tan \beta < 50, \quad 0 \text{ GeV} < M_2, \mu < 800 \text{ GeV}. \quad (7)$$

In our scan we consider the following constraints: (1) $\chi^0_1$ to account for the WMAP measured dark matter relic density at $2\sigma$ level \cite{21}; (2) The LEP lower bounds on the Higgs boson, neutralinos and charginos, including the $Z$-boson invisible decay; (3) The precision EW observables plus $R_b$ \cite{22}. The samples surviving the above constraints will be input for the calculation of the $\tilde{\chi} - N$ scattering rate.

Our scan samples are $10^7$ random points in the parameter space, and about 14000 samples can survive the constraints from the dark matter relic density ($2\sigma$) and the collider experiments. The survived samples are displayed in Fig. 1 in comparison with the MSSM results taken from \cite{6}. From the figure we can see that although the $\tilde{\chi} - N$ scattering cross section is highly suppressed in split-SUSY, still lots of samples can be excluded by the present XENON100 (90% C.L.) limits, and the future exposure of XENON (6000 kg-days) can further cover a large part of the survived parameter space. In case of null results in the future XENON experiment, the remained parameter space is characterized by $50$ GeV $< m_{\tilde{c_1}} < 75$ GeV with $\tilde{\chi}^0_1$ mainly annihilating through exchanging the SM-like Higgs boson to get the measured relic density \cite{23}. 

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FIG. 1: The right (left) panel is the scatter plots of the split-SUSY (MSSM) parameter space which survived the constraints from the dark matter relic density (2σ) and the collider experiments. The ‘+’ points (red) are excluded by XENON100 (90% C.L.) limits, the ‘×’ (blue) will be covered by the future XENON exposure (6000 kg-days), and the ‘◦’ (green) are beyond the future XENON sensitivity.

FIG. 2: Same as the right panel of Fig. 1 but showing $M_1$ versus $\mu$ and $m_{\tilde{\chi}^\pm_1}$ versus the dark matter mass.
In the following we check the properties of the parameter space surviving the present XENON experiment. As shown in Eq.(6), as \( \mu \) approaches downward to \( M_1 \), the coupling \( C_{h\tilde{\chi}\tilde{\chi}} \) can be enhanced. This is reflected in the left panel of Fig.2 where one can learn that, for most points excluded by the present XENON limits or covered by the future XENON exposure, they are in the region of \( M_1 \approx \mu \) so that the \( \tilde{\chi} - N \) scattering cross section is large. In contrast, the remained unaccessible points go into a region (denoted by green ‘o’) in which \( \mu \) is much larger than \( M_1 \). This unaccessible region is shown again in the right panel of Fig. 2 which indicates that \( m_{\chi_1^+} \) is about \( 2m_{\chi^0_1} \). The reason is in this region the lightest neutralino is bino-like and the lightest chargino is wino-like.

![Graph](image)

**FIG. 3:** Same as the right panel of Fig. 1 but showing the bino component of the lightest neutralino.

We show the bino component of the lightest neutralino in Fig. 3 and the higgsino component of the lightest chargino in Fig. 4. From Fig. 3 we see that the neutralino is accessible when its bino component is small (higgsino component is large), while in the unaccessible region the neutralino is highly bino-like. From Fig. 4 we see that in the accessible region the
chargino has a large higgsino component (a small wino component), while in the unaccessible region the chargino has a small higgsino component (a large wino component).

FIG. 4: Same as the right panel of Fig. 1 but showing the higgsino component of the lightest chargino.

Since the lightest neutralino is bino-like except in the $M_1 \simeq \mu$ region, the mass of gluino has an approximate linear relation with $m_{\tilde{\chi}^0}$ which is shown in left panel of Fig. 5. The peak in the plot is the region where the lightest neutralino is higgsino dominant. The dominant production of split-SUSY particles at the LHC is $pp \to \tilde{g}\tilde{g}$, whose cross section is shown in the right panel of Fig. 5. We can see that the region unaccessible at XENON has a large production rate at the LHC. The observability of such a light gluino pair production has been studied in [24], which found $S/\sqrt{B}$ can reach 23 from ATLAS 0-lepton search at the LHC-7 with 5 fb$^{-1}$ integrated luminosity. So we conclude that the LHC and XENON will play complementary roles in testing split-SUSY.

Note that in split-SUSY the neutralino dark matter cannot be as light as several GeV to explain the CoGeNT and DAMA/LIBRA results. As shown in [9], the neutralino dark matter in the MSSM cannot be such light either; only in the framework of the Next-to-Minimal Supersymmetric Model can the dark matter be so light and have a large scattering cross section with the nucleon to explain the CoGeNT and DAMA/LIBRA results.

In conclusion, we studied the present and future XENON limits on the neutralino dark
matter in split-SUSY. We performed a scan over the parameter space under the current constraints from collider experiments and the WMAP measurement of the dark matter relic density. We found that in the allowed parameter space a large part has already been excluded by the present XENON100 limits while a further largish part can be covered by the future exposure (6000 kg-days). In case of unobservation of dark matter in the future exposure of XENON, the lightest neutralino will be constrained to be bino-like and the lightest chargino will be a light wino-like one below 150 GeV.

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