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Cold Dark Matter and Leptogenesis in the SE$_6$SSM †

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Abstract: In the E$_6$ inspired extension of the minimal supersymmetric standard model with an extra U(1)$_N$ gauge symmetry under which right-handed neutrinos have zero charge, a single discrete Z$_H$ symmetry permits suppressing rapid proton decay and non-diagonal flavor transitions. Our analysis demonstrates that in this model (SE$_6$SSM) the appropriate amount of the baryon asymmetry can be induced even for relatively low reheating temperatures $T_R < 10^{6-7}$GeV. We argue that within the variant of the SE$_6$SSM, in which the cold dark matter density is formed by two stable states, there are some regions of the parameter space that are safe from all current constraints.

Keywords: unified field theories and models; models beyond the standard model; supersymmetry; cold dark matter; leptogenesis

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1. Introduction

It is well known that in Grand Unified Theories (GUTs) E$_6$ gauge group can be broken down to SU(3)$_C$ × SU(2)$_W$ × U(1)$_Y$ × U(1)$_N$ at very high energies where

$$U(1)_N = \frac{1}{4}\, U(1)\chi + \frac{\sqrt{15}}{4} U(1)\psi. \quad (1)$$

Here SU(3)$_C$ × SU(2)$_W$ × U(1)$_Y$ is the gauge group of standard model (SM), while U(1)ψ and U(1)χ are associated with the subgroups E$_6$ ⊃ SO(10) × U(1)ψ and SO(10) ⊃ SU(5) × U(1)χ. The exceptional supersymmetric (SUSY) standard model (E$_6$SSM) [1,2] (for recent review, see [3]) implies that around the GUT scale M$_0$ the gauge symmetries U(1)ψ and U(1)χ are broken so that the matter parity $Z_M = (-1)^{3(B-L)}$ is also preserved.

In the E$_6$ inspired U(1)$_N$ extensions of the minimal supersymmetric standard model (MSSM) the right-handed neutrinos do not participate in the gauge interactions and may be superheavy [1,2]. Therefore the successful leptogenesis is a distinctive feature of these models because the heavy Majorana right-handed neutrinos may decay into final states with lepton number L = ± 1, creating a lepton asymmetry in the early Universe [4,5].

In the U(1)$_N$ extensions of the MSSM gauge anomalies get canceled if the particle spectrum at low-energies involves complete representations of E$_6$. Thus to ensure that the E$_6$SSM is anomaly-free one is forced to extend the minimal matter content by extra matter beyond the MSSM which, together with ordinary SM fermions, form three complete 27-plets of E$_6$ (27$_i$ with i = 1,2,3). Each 27-dimensional representations of E$_6$ involves one generation of ordinary matter, a SM singlet field S_i, that carries non-zero U(1)$_N$ charge, up- and down-type Higgs doublets H_{ui} and H_{di} as well as charged ±1/3 exotic quarks D_i and $\overline{D}_i$. The presence of extra exotic matter may give rise to non-diagonal flavor transitions and rapid proton decay. In the E$_6$SSM a set of discrete symmetries can be used to suppress the corresponding operators [1,2].

In this article we explore the leptogenesis and the interactions of the dark matter particles with the nucleons in the modification of the E$_6$SSM (SE$_6$SSM) [6,7] in which a single discrete Z$_H$ symmetry forbids the most dangerous baryon and lepton number violating operators as well as non-diagonal flavor transitions. In the next section we specify the SE_6SSM. In Section 3 the leptogenesis within this model is considered. The dependence of the dark matter-nucleon scattering cross section on the parameters of the SE_6SSM is examined in Section 4. Section 5 concludes the paper.

2. The SE₆SSM

The SE_6SSM implies that below the scale M_0 three complete 27-plets are accompanied by SM singlet superfield ϕ, which does not participate in the E_6 interactions, and a set of pairs of supermultiplets M_l and $\overline{M}_l$, which belong to additional $27_l'$ and $\overline{27}_l'$ representations respectively. Because M_l and $\overline{M}_l$ carry opposite $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N$ quantum numbers gauge anomalies still cancel. In the simplest case the set of M_l and $\overline{M}_l$ involves three pairs of $SU(2)_W$ doublets, i.e., L_4 and $\overline{L}_4$, H_u and $\overline{H}_u$, H_d and $\overline{H}_d$, as well as a pair of superfields S and $\bar{S}$. The field content of the SE_6SSM may originate from the E_6 orbifold GUT model in six dimensions in which the appropriate splitting of the bulk 27′ supermultiplets can be achieved [6].

The supermultiplets ϕ, S, $\bar{S}$, H_u, H_d, L_4 and $\overline{L}_4$ are required to be even under the Z^H symmetry whereas all other supermultiplets are odd [7]. $\overline{H}_u$, and $\overline{H}_d$ get combined with the superposition of the corresponding components from the 27_i, forming vectorlike states with masses of order M_0. The components of the supermultiplets L_4 and $\overline{L}_4$, as well as S and $\bar{S}$ are expected to gain the TeV scale masses. The presence of L_4 and $\overline{L}_4$, at low energies permits the lightest exotic quarks to decay within a reasonable time and facilitates the gauge coupling unification in the model under consideration [6].

In the simplest phenomenologically viable scenario the lightest SUSY particles that are linear superpositions of the fermion components of the superfields S_i, have masses which are much smaller than 1 eV. These lightest exotic fermions form hot dark matter in our Universe. Nevertheless they give only a minor contribution to the total density of dark matter. The existence of neutral fermions with tiny masses may lead to very interesting implications for the neutrino physics [8].

To avoid the appearance of the lightest exotic fermions with tiny masses in the particle spectrum here we assume that at least three E_6 singlet superfields ϕ_i survive below the scale M_0 [9]. These three superfields should be odd under the Z^H symmetry. The part of the superpotential W_{IH} that describes the interactions of ϕ_i, S_i, $H_{u\alpha}$ and $H_{d\alpha}$ with the Z^H even supermultiplets ϕ, S, $\bar{S}$, H_u and H_d can be presented in the following form

$$W_{IH} = \widetilde{M}_{ij}\phi_i\phi_j + \tilde{k}_{ij}\phi\phi_i\phi_j + \tilde{\lambda}_{ij}\bar{S}\phi_i S_j + \lambda_{\alpha\beta}S(H_{d\alpha}H_{u\beta}) + \tilde{f}_{i\alpha}S_i(H_{d\alpha}H_u) + f_{i\alpha}S_i(H_d H_{u\alpha}), \tag{2}$$

where i, j=1, 2, 3 and α, β=1, 2. In this variant of the SE_6SSM the sector responsible for the breakdown of the gauge symmetry is formed by the scalar components of ϕ, S, $\bar{S}$, H_u and H_d. If superfields S and $\bar{S}$ develop vacuum expectation values (VEVs) along the D-flat direction, i.e., $< S > \approx < \bar{S} > \approx S_0$, then the value of S_0 can be much larger than the sparticle mass scale M_S resulting in an extremely heavy Z′ boson. All extra exotic states may be also rather heavy in this limit.

The conservation of Z^M and Z^H symmetries implies that R-parity and Z^E symmetry are also conserved where $Z^H = Z^M \times Z^E$ [6]. Here we focus on the scenarios in which gravitino is the lightest R-parity odd state. Therefore it has to be stable and potentially contributes to the density of dark matter. Since gravitino is the lightest SUSY particle with $Z^E = +1$ the lightest exotic state with $Z^E = -1$ must be absolutely stable as well [6]. In this paper we restrict our consideration to the scenarios when the lightest stable exotic state is predominantly formed by the fermion components of $H_{u\alpha}$ and $H_{d\alpha}$.

In order to find a viable cosmological scenarios with stable gravitino one has to ensure that the decay products of the lightest unstable R-parity odd (or exotic) particle Υ do not alter the abundances of light elements induced by the Big Bang Nucleosynthesis (BBN). The decays of state Υ change the abundances of light elements the more the longer its lifetime τ is. This problem can be evaded if particle Υ decays before BBN, i.e., $\tau < 1$ s.

The lifetime of state Υ decaying into its SM partner (or lightest exotic fermion) and gravitino can be estimated as [10]

$$\tau \sim 48\pi \,\frac{(m_{3/2}M_P)^2}{M_{\Upsilon}{}^5}, \tag{3}$$

where M_{Υ} is its mass, $m_{3/2}$ is a gravitino mass and M_P=$(8\pi\, G_N)^{-1/2}$=$2.4\cdot 10^{18}$ GeV is the reduced Planck mass. To get $\tau < 1$ sec. for $M_{\Upsilon} \approx 1$ TeV one needs $m_{3/2} < 1$ GeV.

If gravitinos mostly originate from scattering processes of particles in the thermal bath then their abundance is approximately proportional to the reheating temperature T_R after inflation. In the leading approximation one finds [11,12]

$$\Omega_{3/2}h^2 \sim 0.27\,\left(\frac{T_R}{10^8 GeV}\right)\left(\frac{1\,GeV}{m_{3/2}}\right)\left(\frac{M_g}{1\,TeV}\right)^2. \tag{4}$$

Here M_g is a gluino mass. Since $\Omega_{3/2}h^2 \leq 0.12$ [13], for $M_g \geq 3$ TeV and $m_{3/2} \approx 1$ GeV one obtains an upper bound on the reheating temperature, i.e., $T_R < 10^{6-7}$ GeV [14].

3. Leptogenesis

Even for so low reheating temperatures the appropriate amount of the baryon asymmetry can be induced within the SE$_6$SSM via the decays of the lightest right-handed neutrino/sneutrino. In this SUSY model the part of the superpotential W_N that describes the interactions of the right-handed neutrino superfields N_i is given by

$$W_N = \frac{1}{2}M_i N_i N_i \;+\; \tilde{h}_{ij}N_i(H_u L_j) + \;h_{i\alpha}N_i(H_{u\alpha}L_4). \tag{5}$$

Here L_j are the left-handed lepton doublets whereas i, j = 1, 2, 3 and α =1, 2. After inflation lightest right-handed neutrino/sneutrino with mass M_1 may be produced by thermal scattering if $T_R > M_1$. To guarantee that thermal leptogenesis can take place we fix $M_1 = 10^5$ GeV. We also assume that two other right-handed neutrino states and their superpartners have masses $M_{2,3}$~10^{6-7}GeV so that $M_1 \ll M_2 \ll M_3$ while the sparticle mass scale M_S is lower than 10 TeV. For so low M_i the absolute values of the Yukawa couplings $\tilde{h}_{ij}$ must be rather small to reproduce the left-handed neutrino mass scale $m_\nu \leq 0.1$ eV, i.e., $|\tilde{h}_{ij}|^2 \ll 10^{-8}$. So small Yukawa couplings can be ignored in the leading approximation

Then the process of generation of lepton asymmetry is controlled by the set of CP (decay) asymmetries induced by the last term in W_N. In particular, the CP asymmetries associated with the decays of the lightest right-handed neutrino N_1 are defined as

$$\varepsilon_{1,\alpha} = \frac{\Gamma_{1\alpha}-\bar{\Gamma}_{1\alpha}}{\sum_\beta(\Gamma_{1\beta}+\bar{\Gamma}_{1\beta})}, \qquad \varepsilon_{1,\tilde{\alpha}} = \frac{\Gamma_{1\tilde{\alpha}}-\bar{\Gamma}_{1\tilde{\alpha}}}{\sum_\beta(\Gamma_{1\tilde{\beta}}+\bar{\Gamma}_{1\tilde{\beta}})}, \tag{6}$$

where $\Gamma_{1\alpha}(\bar{\Gamma}_{1\alpha})$ are partial widths of the decays of N_1 into fermion components of L_4 and scalar components of $H_{u\alpha}$ (into their antiparticles) and $\Gamma_{1\tilde{\alpha}}(\bar{\Gamma}_{1\tilde{\alpha}})$ are partial widths of the decays of N_1 into scalar components of L_4 and fermion components of $H_{u\alpha}$ (into their antiparticles). Similarly, one can define decay asymmetries $\varepsilon_{\tilde{1},\alpha}$ and $\varepsilon_{\tilde{1},\tilde{\alpha}}$ that correspond to the decays of the lightest right-handed neutrino $\widetilde{N}_1$ [5].

At the tree level all CP asymmetries vanish. The non-zero values of the decay asymmetries arise after the inclusion of one-loop vertex and self-energy corrections to the decay amplitudes of N_1 and $\widetilde{N}_1$. In this context it is worth noting that the supermultiplets $H_{u\alpha}$ can be redefined so that only one doublet H_{u1} interacts with L_4 and N_1. Therefore h_{12} in W_N may be set to zero. In this limit $\varepsilon_{1,2} = \varepsilon_{1,\tilde{2}} = \varepsilon_{\tilde{1},2} = \varepsilon_{\tilde{1},\tilde{2}}$ =0. When sparticle mass scale M_S is negligibly small as compared with M_1, $h_{j1} = |h_{j1}|e^{i\varphi_{j1}}$ and M_j are real, the non-zero CP asymmetries are given by

$$\varepsilon_{1,1} = \varepsilon_{1,\tilde{1}} = \varepsilon_{\tilde{1},1} = \varepsilon_{\tilde{1},\tilde{1}} = \frac{1}{8\pi}\left[\sum_{j=2,3}|h_{j1}|^2 f\left(\frac{M_j^2}{M_1^2}\right)\sin 2\Delta\varphi_{j1}\right], \tag{7}$$

where $\Delta\varphi_{j1} = \varphi_{j1} - \varphi_{11}$ and $f(z) = \frac{2\sqrt{z}}{1-z} - \sqrt{z}\ln\frac{1+z}{z}$.

The evolution of the U(1)$_{B-L}$ asymmetries is described by the system of Boltzmann equations. The induced baryon asymmetry can be estimated as follows

$$Y_{\Delta B} \sim 10^{-3}\varepsilon_{1,1}\eta, \qquad Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s}|_0 = (8.75 \pm 0.23)\cdot 10^{-11}, \tag{8}$$

where $Y_{\Delta B}$ is the baryon asymmetry relative to the entropy density and η is an efficiency factor that varies from 0 to 1. In the strong washout scenario η is given by

$$\eta = \frac{H(T=M_1)}{\Gamma_1}, \qquad H = 1.66\sqrt{g_*}\frac{T^2}{M_{Pl}}, \qquad \Gamma_1 = \Gamma_{11} + \bar{\Gamma}_{11} = \frac{|h_{11}|^2}{8\pi}M_1, \tag{9}$$

Here M_{Pl}=1.22·10^{19} GeV, H is the Hubble expansion rate, $g_* = n_b + \frac{7}{8}n_f$ is the number of relativistic degrees of freedom. In the SE$_6$SSM g_* = 360.

As follows from Equation (7) the values of the CP asymmetries are determined by the CP-violating phases $\Delta\varphi_{j1}$ and the absolute values of the Yukawa couplings $|h_{21}|$ and $|h_{31}|$ but do not depend on $|h_{11}|$. To simplify our analysis we set $|h_{31}| = 0$ and $M_2 = 10\cdot M_1$. Then for $\Delta\varphi_{21} = \pi/4$ we find that $\varepsilon_{1,1}$ changes from 10^{-6} to 10^{-4} if $|h_{21}|$ varies from 0.01 to 0.1. At the same time the efficiency factor η is set by M_1 and $|h_{11}|$. We restrict our consideration here by the values of $|h_{11}|^2 \geq 10^{-8} \gg |\tilde{h}_{ij}|^2$. In this case for $M_1 = 100$ TeV η varies from 6.5×10^{-4} to 6.5×10^{-6} when $|h_{11}|$ increases from 10^{-4} to 10^{-3}. Thus the observed baryon asymmetry can be reproduced if $\frac{|h_{11}|}{|h_{21}|} \sim 0.01$.

4. Dark Matter-Nucleon Scattering cross Section

The scalar components of the supermultiplets ϕ_i, S_i, $H_{u\alpha}$ and $H_{d\alpha}$ do not develop VEVs. Their fermion components compose the exotic chargino and neutralino states. In the limit, when all components of ϕ_i are considerably heavier than the bosons and fermions from the supermultiplets S_i, $H_{u\alpha}$ and $H_{d\alpha}$ the superfields ϕ_i can be integrated out so that the part of the SE$_6$SSM superpotential (2) reduces to

$$W_{IH} \to \widetilde{W}_{IH} \simeq \tilde{\mu}_{ij}S_i S_j + \lambda_{\alpha\beta}S(H_{d\alpha}H_{u\beta}) + \tilde{f}_{i\alpha}S_i(H_{d\alpha}H_u) + f_{i\alpha}S_i(H_d H_{u\alpha}). \tag{10}$$

One can always choose the field basis in which $\tilde{\mu}_{ij} = \tilde{\mu}_i\delta_{ij}$ and $\lambda_{\alpha\beta} = \lambda_{\alpha\alpha}\delta_{\alpha\beta}$. Here it is expected that the lightest exotic state with $Z_E = -1$ is predominantly composed of the fermion components of the supermultiplets H_{u1} and H_{d1} while all sparticles except gravitino and all other exotic states have masses which are much larger than 1 TeV. We also assume that H_{u1} and H_{d1} mostly interact with H_u, H_d and S_1, whereas all other couplings of H_{u1} and H_{d1} are negligibly small. In this case the mass of the charged fermion components of H_{u1} and H_{d1} is determined by $\mu_{11} = \lambda_{11} < S >$, i.e., $m_{\chi_1^\pm} = |\mu_{11}|$. The neutral fermion components of these supermultiplets form two Majorana states with masses m_{χ_2} and m_{χ_1}. When $|\tilde{\mu}_1|$ is much larger than $|\mu_{11}|$, $< H_d > = v_1$ and $<H_u> = v_2$ the masses m_{χ_2} and m_{χ_1} are rather close to $|\mu_{11}|$ and the mass of the lightest exotic state is given by

$$m_{\chi_1} \simeq |\mu_{11}| - \Delta_1, \qquad \Delta_1 \simeq \frac{(\tilde{f}_{11}v_2 + f_{11}v_1)^2}{2(|\tilde{\mu}_1| - |\mu_{11}|)} \tag{11}$$

Because in the scenarios under consideration the lightest neutral exotic fermion is stable its contribution to the cold dark matter relic density can be estimated using the approximate formula

$$\Omega_{\tilde{H}}h^2 \simeq 0.1\left(\frac{|\mu_{11}|}{1\ \text{TeV}}\right)^2, \tag{12}$$

which was derived in the case of the Higgsino dark matter within the MSSM (see [15]). On the hand the Planck observations lead to $(\Omega h^2)_{exp} = 0.1188 \pm 0.0010$ [13]. Thus in the phenomenologically viable scenarios $|\mu_{11}|$ is expected to be lower than 1.1 TeV. If

$|\mu_{11}| < 1.1$ TeV then gravitino may account for some or major part of the observed cold dark matter density.

Since the couplings of gravitino to the SM particles are negligibly small, in the scenarios under consideration the interactions of the cold dark matter with the baryons are determined by the couplings of the lightest neutral exotic fermion χ_1. In both the MSSM and SE6SSM the dominant contribution to the spin-independent (SI) dark matter-nucleon scattering cross section σ_{SI} comes from the t-channel exchange of the lightest CP-even Higgs boson h_1. Therefore in the leading approximation σ_{SI} takes the form

$$\sigma_{SI} = \frac{2(m_r m_N)^2}{\pi v^2 m_{h_1}^4} |g_{h_1\chi_1\chi_1}|^2 |F^N|^2, \qquad m_r = \frac{m_{\chi_1} m_N}{m_{\chi_1}+m_N}, \quad F^N = \sum_{q=u,d,s} f_{Tq}^N + \frac{2}{27}\sum_{Q=c,b,t} f_{TQ}^N \tag{13}$$

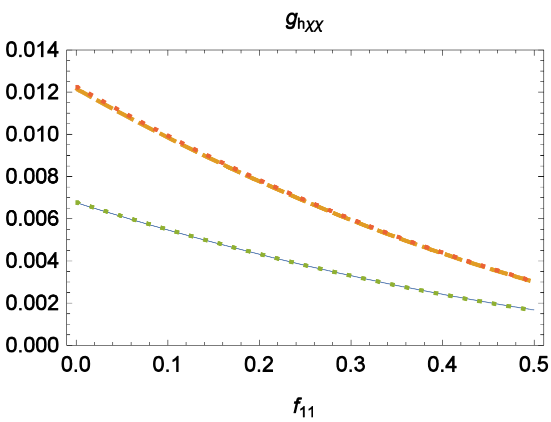
where m_{h_1} and m_N are the mass of the lightest Higgs scalar and nucleon mass respectively, $v = \sqrt{v_1^2+v_2^2} \simeq 174$ GeV, $g_{h_1\chi_1\chi_1}$ is the coupling of h_1 to χ_1

$$m_N f_{Tq}^N = \langle N | m_q \bar{q} q | N \rangle, \qquad f_{TQ}^N = 1 - \sum_{q=u,d,s} f_{Tq}^N, \qquad g_{h_1\chi_1\chi_1} \simeq \frac{\Delta_1}{\sqrt{2}v}. \tag{14}$$

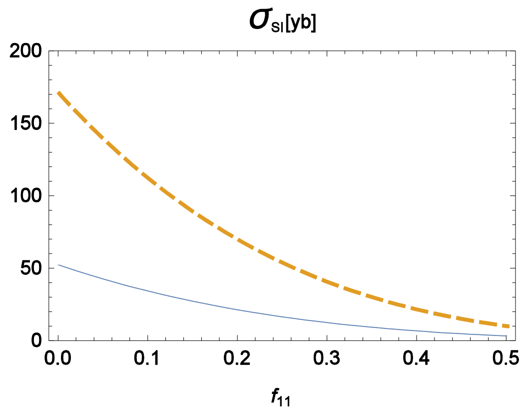
From Equation (13) one can see that σ_{SI} depends rather strongly on the hadronic matrix elements, i.e., f_{Tq}^N. Here we set $f_{Tu}^N \simeq 0.0153$, $f_{Td}^N \simeq 0.0191$ and $f_{Ts}^N \simeq 0.0447$. These values of the hadronic matrix elements are the default values used in micrOMEGAs [16].

Instead of v_1 and v_2 it is more convenient to use $\tan\beta = \frac{v_2}{v_1}$ and v. To simplify our analysis we set $\tan\beta \simeq 2$ and $\tilde{\mu}_1 \simeq 2$ TeV. In order to avoid the experimental lower limit on the mass of the lightest exotic chargino and to ensure that χ_1 gives rise to the phenomenologically acceptable dark matter density the interval of variation of μ_{11} is chosen so that $\mu_{11} \geq 200$ GeV and $\mu_{11} \leq 1$ TeV. The results of our analysis are presented in Figure 1. The values of σ_{SI} shown in Figure 1 remain always smaller than 60 yb for $m_{\chi_1} \simeq \mu_{11} = 200$ GeV and 300 yb for $m_{\chi_1} \simeq \mu_{11} = 1$ TeV which are the values of the experimental bounds on σ_{SI} obtained by the LUX-ZEPLIN (LZ) experiment [17].

The values of σ_{SI} presented in Figure 1 are substantially smaller than its maximal possible value in the SE6SSM. In the part of the parameter space examined in Figure 1 the suppression of σ_{SI} is caused by large $\tilde{\mu}_1$, which is associated with the sparticle mass scale, as well as by the partial cancellations of different contributions to $g_{h_1\chi_1\chi_1}$. The maximal possible value of σ_{SI} is attained when $\tilde{\mu}_1 \simeq \mu_{11}$ and $f_{11} \sim \tilde{f}_{11} \sim 1$. In this case σ_{SI} can reach 20–30 zb which is two orders of magnitude larger than the present experimental limit [17].



(**a**)



(**b**)

Figure 1. (**a**) The coupling $g_{h_1\chi_1\chi_1}$ and (**b**) the cross-section σ_{SI} as a function of f_{11} for $\tilde{f}_{11}$=-0.5, $\tan\beta \simeq 2$, $\tilde{\mu}_1 = 2$ TeV, $\mu_{11} = 200$ GeV (solid lines) and $\mu_{11} = 1$ TeV (dashed lines).

5. Conclusions

In this paper we argued that the appropriate value of the baryon asymmetry can be induced within the $U(1)_N$ extensions of the MSSM, in which single discrete Z_H symmetry forbids flavor-changing transitions and the most dangerous baryon and lepton number violating operators, i.e., SE$_6$SSM, even if the reheating temperature $T_R < 10^{6-7}$ GeV. Here we explored the variant of the SE$_6$SSM with two stable neutral states that form cold dark matter density. Since no firm indication of the presence of dark matter has been observed at the direct detection experiments we assumed that one of these stable states is gravitino with mass $m_{3/2} < 1$ GeV. Another stable state tends to be the lightest exotic neutralino which is mostly composed of the neutral fermion components of the $SU(2)_W$ doublets. In this case the lightest and second lightest exotic neutralino states ($\chi_1$and χ_2) as well as the the lightest exotic chargino $\chi_1^{\pm}$ are almost degenerate. If these exotic fermions are lighter than 1.1 TeV they can lead to the phenomenologically acceptable density of the cold dark matter. Several collider experiments have searched for such particles. However because the mass splitting between these states is small the decay products of χ_2 and $\chi_1^{\pm}$ are too soft so that they escape detection if $m_{\chi_1} \approx m_{\chi_2} \approx m_{\chi_1^{\pm}} \geq 200$ GeV. Our analysis indicates that there is a part of the SE$_6$SSM parameter space in which the SI dark matter-nucleon scattering cross section σ_{SI} can be considerably smaller than the experimental limits. In the near future the experiments XENONnT [18] and LZ [19] may set even more stringent bounds on σ_{SI} constraining further the SE$_6$SSM parameter space.

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References

1. King, S.F.; Moretti, S.; Nevzorov, R. Theory and phenomenology of an exceptional supersymmetric standard model. *Phys. Rev. D* **2006**, *73*, 035009.
2. King, S.F.; Moretti, S.; Nevzorov, R. Exceptional supersymmetric standard model. *Phys. Lett. B* **2006**, *634*, 278.
3. King, S.F.; Moretti, S.; Nevzorov, R. A Review of the Exceptional Supersymmetric Standard Model. *Symmetry* **2020**, *12*, 557.
4. Hambye, T.; Ma, E.; Raidal, M.; Sarkar, U. Allowable low-energy E_6 subgroups from leptogenesis. *Phys. Lett. B* **2001**, *512*, 373.
5. Nevzorov, R. Leptogenesis as an origin of hot dark matter and baryon asymmetry in the E_6 inspired SUSY models. *Phys. Lett. B* **2018**, *779*, 223.
6. Nevzorov, R. E_6 inspired supersymmetric models with exact custodial symmetry. *Phys. Rev. D* **2013**, *87*, 015029.
7. Athron, P.; Muhlleitner, M.; Nevzorov, R.; Williams, A.G. Non-Standard Higgs Decays in U(1) Extensions of the MSSM. *JHEP* **2015**, *1501*, 153.
8. Frere, J.M.; Nevzorov, R.B.; Vysotsky, M.I. Stimulated neutrino conversion and bounds on neutrino magnetic moments. *Phys. Lett. B* **1997**, *394*, 127.
9. Nevzorov, R. On the Suppression of the Dark Matter-Nucleon Scattering Cross Section in the SE$_6$SSM. *Symmetry* **2022**, *14*, 2090.
10. Feng, J.L.; Su, S.; Takayama, F. Supergravity with a gravitino LSP. *Phys. Rev. D* **2004**, *70*, 075019.
11. Bolz, M.; Brandenburg A.; Buchmuller, W. Thermal production of gravitinos. *Nucl. Phys. B* **2001**, *606*, 518.
12. Eberl, H.; Gialamas, I.D.; Spanos, V.C. Gravitino thermal production revisited. *Phys. Rev. D* **2021**, *103*, 075025.
13. Ade, P.A.; Aghanim, N.; Arnaud, M.; Ashdown, M.; Aumont, J.; Baccigalupi, C.; Matarrese, S. The Planck collaboration. Planck 2015 results. XIII. Cosmological parameters. *Astron. Astrophys.* **2016**, *594*, A13.
14. Hook, A.; McGehee R.; Murayama, H. Cosmologically Viable Low-energy Supersymmetry Breaking. *Phys. Rev. D* **2018**, *98*, 115036.
15. Arkani-Hamed, N.; Delgado, A.; Giudice, G.F. The Well-tempered neutralino. *Nucl. Phys. B* **2006**, *741*, 108.
16. Belanger, G.; Boudjema, F.; Pukhov, A.; Semenov, A. micrOMEGAs3: A program for calculating dark matter observables. *Comput. Phys. Commun.* **2014**, *185*, 960.
17. Aalbers, J.; Akerib, D.S.; Akerlof, C.W.; Al Musalhi, A.K.; Alder, F.; Alqahtani, A.; Kraus, H. First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment. *arXiv* **2022**, arXiv:2207.03764.

18. Aprile, E.; Aalbers, J.; Agostini, F.; Alfonsi, M.; Althueser, L.; Amaro, F.D.; Zopounidis, J.P. WIMP sensitivity of the XENONnT dark matter experiment. *JCAP* **2020**, *11*, 031.
19. Akerib, D.S.; Akerlof, C.W.; Alsum, S.K.; Araújo, H.M.; Arthurs, M.; Bai, X.; Taylor, D.J. Projected WIMP sensitivity of the LUX-ZEPLIN dark matter experiment. *Phys. Rev. D* **2020**, *101*, 052002.