The supersymmetric Standard Models with decaying and stable dark matters

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Abstract We propose two supersymmetric Standard Models (SMs) with decaying and stable dark matter (DM) particles. To explain the SM fermion masses and mixings and have a heavy decay DM particle $S$, we consider the Froggatt–Nielsen mechanism by introducing an anomalous $U(1)_X$ gauge symmetry. Around the string scale, the $U(1)_X$ gauge symmetry is broken down to a $Z_2$ symmetry under which $S$ is odd while all the SM particles are even. $S$ obtains a vacuum expectation value around the TeV scale, and then it can three-body decay dominantly to the second/third family of the SM leptons in Model I and to the first family of the SM leptons in Model II. Choosing a benchmark point in the constrained minimal supersymmetric SM with exact R parity, we show that the lightest neutralino DM is consistent with the CDMS II experiment. Considering $S$ three-body decay and choosing suitable parameters, we show that the PAMELA and Fermi-LAT experiments and the PAMELA and ATIC experiments can be explained in Model I and Model II, respectively.

1 Introduction

It is well known that supersymmetry provides an elegant solution to gauge hierarchy problem in the Standard Model (SM). In the Minimal Supersymmetric Standard Model (MSSM), gauge coupling unification can be realized, which give us the important hint of Grand Unified Theory (GUT). In addition, in the supersymmetric SMs, we can define a $Z_2$ symmetry called R parity under which the SM particles are even while their supersymmetric partners are odd. With R parity, we can avoid the dimension-four proton decay problem and evade the stringent constraints from the electroweak precision data naturally. Interestingly, the lightest supersymmetric particle (LSP) is stable due to the R parity, and then can be the dark matter (DM) candidate. For example, the lightest neutralino can be a viable cold DM candidate, which can give us the correct relic density as well.

During the last two years, there were quite a few very interesting DM experiments from indirect and direct detections. The ATIC [1] and PPB-BETS [2] collaborations have reported the measurements of cosmic ray (CR) electron/positron spectra at energies up to $\sim 1$ TeV. These data show an obvious excess over the expected background in the energy ranges $\sim 300–800$ GeV and $\sim 500–800$ GeV, respectively. In the mean time, the PAMELA collaboration also released their first CR measurements of the positron fraction [3] and the $\bar{p}/p$ ratio [4]. Although the $\bar{p}/p$ ratio is consistent with the astrophysical expectation from the interactions between the CR nuclei and interstellar medium, the positron fraction indeed shows a significant excess for energies above 10 GeV up to $\sim 100$ GeV, compared to the background predicted by the conventional CR propagation models. Later, the Fermi-LAT collaboration has released data on the measurement of the electron/positron spectrum from 20 GeV to 1 TeV with unprecedented precision [5], and the HESS collaboration has released the data on the measurements of electron/positron spectrum from 340 GeV to 700 GeV [6], complementing their earlier measurements from 700 GeV to 5 TeV [7]. For simplicity, we will denote the Fermi-LAT collaboration as FERMI collaboration in the following. Although the corresponding data from the ATIC and the FERMI/HESS experiments are not fully consistent, it was shown that the DM models, where the DM particles annihilate or decay dominantly to the SM leptons, can explain these experiments by choosing the suitable DM particle mass and the proper final state particles.

To explain the PAMELA/ATIC experiments or the PAMELA/FERMI/HESS experiments from DM annihilations, we know that a large boost factor about 100–1000 is needed. However, from astrophysics, the N-body simulation shows that the boost factor from DM substructure can never

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be larger than 10 \([8]\). To solve this problem, one can consider the Sommerfeld enhancement \([9–12]\) or Breit–Wigner resonant enhancement \([13–16]\). Alternatively, we can also consider the non-thermal dark matter production so that the DM annihilation cross section can be large \([17]\). In addition, if the DM particle is not absolutely stable and can decay dominantly to leptons, we can explain these experiments for the DM lifetime at the order \(\tau \sim 10^{25–10^{27}} \) s \([18–25]\). In particular, in the supersymmetric Standard Models, the LSP neutralino cannot explain the PAMELA/ATIC experiments or the PAMELA/FERMI/HESS experiments unless it can decay due to the suitable \(R\)-parity violation dimension-four operators. Furthermore, to fit the PAMELA and ATIC data via the Markov Chain Monte Carlo (MCMC) technique, one found that the DM mass is about 700 GeV for annihilation and 1.4 TeV for decay, and the favored final state is \(e^+e^-\) \([26]\). And to fit the PAMELA, FERMI, and HESS data, one found that the DM mass is about 2 TeV for annihilation and 4 TeV for decay, and the favored final states are the combination of \(\mu^+\mu^-\) and \(\tau^+\tau^-\) since the electron/positron spectra in the Fermi and HESS experiments are softer than these in the ATIC and PPB-BETS experiments \([26]\). Also, the HESS observation of the Galactic center gamma rays gives strong constraint on the annihilation DM scenario while gives much weaker constraint on the decay DM scenario. Thus, it favors the decay DM \([26]\).

Recently, the Cryogenic Dark Matter Search (CDMS) collaboration has observed two candidate DM events in the CDMS II experiment \([27]\). The recoil energies for these two events are 12.3 keV and 15.5 keV, respectively, and the data set an upper limit on the DM-nucleon elastic-scattering spin independent cross section is about \(10^{-8–10^{-7}} \) pb. Because the probability of observing two or more background events is 23%, the CDMS II results cannot be a statistically significant evidence for DM interactions, but these two events cannot be rejected as signal. In particular, the favored DM mass from the CDMS II data is about 100 GeV. Later, the CDMS II results have been studied extensively in various DM models \([28–46]\). Interestingly, the CDMS II experiment can be explained in the supersymmetric Standard Models where the LSP neutralino is DM.

In short, if the PAMELA, ATIC, FERMI, and HESS experiments indeed observed the DM annihilations or decays, the corresponding DM particle is heavy around a few TeVs. And if the two events observed by the CDMS II experiment are DM signals, the corresponding DM particle is light around 100 GeV. Therefore, there may exist at least two DM particles in the Nature. In fact, in almost all the previous DM models, the nearly universal implicit assumption is that there is one and only one DM particle. However, we cannot prove this implicit assumption, and then we cannot ignore the possibility of multicomponent DM \([47–60]\).

In this paper, we propose two supersymmetric Standard Models with decaying and stable DM particles. To avoid the proton decay problem and evade the stringent constraints from the electroweak precision data, we assume that \(R\) parity is not violated. In our models, we require that the LSP neutralino be the stable DM particle with mass around 100 GeV and the LSP neutralino–nucleon scattering cross section be about \(10^{-8–10^{-7}} \) pb. Thus, we can explain the CDMS II experiment. We also assume that the supersymmetry breaking scale is still below 1 TeV, and then we can solve the gauge hierarchy problem without fine-tuning. To explain the PAMELA, ATIC, and FERMI experiments, we introduce a DM particle \(S\) with mass around a few TeVs. To produce the SM fermion masses and mixings and have the heavy decay DM particle \(S\), we consider the Froggatt–Nielsen (FN) mechanism \([61]\). We introduce an anomalous \(U(1)_X\) gauge symmetry whose anomaly is canceled by the Green–Schwarz mechanism \([62]\). Especially, the \(U(1)_X\) gauge symmetry is broken down to the \(Z_2\) symmetry around the string scale under which \(S\) is odd while all the SM particles are even. Thus, \(S\) can be a DM particle. Similar to the discussions in Refs. \([63–73]\), the SM fermion masses and mixings can be generated as well. With a pair of heavy vector-like particles that are SM singlets and have \(U(1)_Y\) charges \(\pm 1\) respectively, we obtain that the leading Yukawa coupling terms between \(S\) and the SM particles are \(S^2H_dL_iE^c_j\) where \(H_d\) is the Higgs field, and \(L_i\) and \(E^c_j\) are the \(i\)-th family of the SM lepton doublet and \(j\)-th fermion of the right-handed charged lepton, respectively. In Model I, we have \((i, j) = (2, 2)\) and \((3, 2)\), while in Model II, we have \((i, j) = (1, 1)\). After \(S\) obtains a vacuum expectation value (VEV) at the TeV scale, \(S\) can decay dominantly to the second/third family of the SM leptons via dimension-six operators (three-body decay) in Model I, and to the first family of the SM leptons in Model II. To realize our idea, we present a benchmark point from the constrained minimal supersymmetric Standard Model (CMSSM). The lightest neutralino \(\tilde{\chi}^0_1\) contributes to part of the whole DM relic density, i.e., \(\Omega h^2 \approx 0.08\). The LSP neutralino–nucleon elastic-scattering spin independent cross section is about \(5 \times 10^{-9} \) pb. Thus, this benchmark point is consistent with the CDMS II results. In addition, for the \(S\) lifetime about \(\tau \sim 10^{25–10^{27}}\) s, we can explain the PAMELA, FERMI and CDMS II experiments in Model I with \(S\) mass 3 TeV, and explain the PAMELA, ATIC and CDMS II experiments in Model II with \(S\) mass 1.8 TeV.

The paper is organized as follows. In Sect. 2, we explain the SM fermion masses and mixings as well as the leading Yukawa terms \(S^2H_dL_iE^c_j\) via the FN mechanism. In Sect. 3, we present a benchmark point in the CMSSM parameter space, and we discuss the DM particle \(S\) three-body cascade decay. We fit the PAMELA and FERMI data and the PAMELA and ATIC data in Sect. 4. Section 5 is our discussion and conclusions. We present more technical details in Appendices A, B, and C.