Semielastic Dark Matter

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Many models have recently been proposed in which dark matter (DM) couples to Standard Model fields via a GeV-scale dark sector. We consider scenarios of this type where the DM mass, at the electroweak/TeV scale, is generated by the VEV of a singlet which also couples to the Higgs. Such a setup results in a distinct recoil spectrum with both elastic and inelastic components. We construct an explicit NMSSM-like realization of this setup, discuss constraints coming from the relic density, and include benchmark points which are consistent with current limits, yet visible at upcoming direct detection experiments.

I. INTRODUCTION

By now, there is overwhelming evidence supporting the existence of particle dark matter (DM). Many models incorporate DM into proposals for new TeV-scale physics, with recent efforts focusing on the possibility that DM may also interact with a dark sector, composed of new gauge groups and light (GeV-scale) degrees of freedom. These models attribute positron/electron cosmic ray excesses \[1\] to the annihilation \[20\] or decay of \[7\] of DM via the new GeV-scale states. In effect, the dark sector serves as a restrictive portal, allowing DM to decay/annihilate to light leptons, but not into (unobserved) protons and anti-protons. Dark sectors can also naturally induce an \(O(100)\) keV mass splitting between the DM states \[2\]. Consequently, if the fields mediating the scattering of DM with atomic nuclei couple off-diagonally to different DM states, the result is a novel inelastic recoil spectrum \[9\] which has been used to explain the DAMA results \[10\]. Indeed, regardless of any DAMA signal, inelastic scattering is a generic consequence of dark sectors which can be probed by upcoming experiments.

The phenomenology summarized above follows from the connection between GeV-scale fields and the Standard Model (SM). But this is unlikely to be the whole story, because we would like the TeV-scale mass of DM to be related to the scale of electroweak symmetry breaking. The simplest way to generate the mass of DM is to couple it to a singlet that also couples to the SM-Higgs and receives a TeV-scale VEV \[3, 11\]. This naturally allows DM to scatter elastically off of atomic nuclei via the exchange of a Higgs/singlet. We find that such dark sector models yield a distinct recoil spectrum, with both elastic and inelastic components, visible at the next generation of direct detection experiments such as XENON100.

This paper is structured as follows. In Sec. \[1\] we introduce this new recoil spectrum and survey its unique features. In Sec. \[11\] we construct an explicit NMSSM-like model realizing the scenario we propose, and discuss the constraints imposed on it from considerations of the relic density. In Sec. \[14\] we discuss the masses and couplings of the model in a convenient limit, and present several benchmark points. Sec. \[1\] contains our conclusions.

II. SEMI-ELASTIC SCATTERING

The elastic scattering of DM with atomic nuclei can be a natural consequence of the mechanism setting its TeV-scale mass. We will illustrate this in an especially simple setup by coupling DM and the Higgs to the same singlet field. While we will work in a supersymmetric framework, our results are easily generalized to other scenarios.

Consider the superpotential

\[ W = \lambda S H_d \cdot H_u + \eta S \chi \bar{\chi}, \tag{1} \]

where \(H_d\) and \(H_u\) are the two Higgs doublet fields, \(S\) is the NMSSM singlet \[16\], and \(\chi/\bar{\chi}\), which are oppositely charged under a dark sector gauge symmetry, will compose our DM candidate. After electroweak symmetry breaking, \(S\) receives a VEV, which generates a supersymmetric mass for the DM fields, \(m_\chi = \eta \langle S \rangle\). Taking DM to be a scalar component of \(\chi/\bar{\chi}\) (we will justify this assumption in the next section), we see that the \(F\)-term
potential includes a direct coupling between DM and the Higgs, $|FS|^2 \supset \chi \chi H_u^* H_d^* + h.c.$ This coupling allows the Higgs to mediate the elastic scattering of DM against nuclei. A second contribution to elastic scattering is mediated by the singlet $S$, which mixes with the Higgs after electroweak symmetry breaking.

At the same time, other dark sector interactions can lead to an inelastic component of scattering. We consider the class of models where DM is charged under a GeV scale dark sector, with a $U(1)_{d}$ gauge factor that kinetically mixes with hypercharge,

$$\mathcal{L} \supset \frac{\epsilon}{2} B^\mu \epsilon_{\mu \nu} + g_d \epsilon^\mu (\chi_0 \partial_\mu \chi_1 - \chi_1 \partial_\mu \chi_0).$$

(2)

Here $\chi_{0,1}$ are the two real scalar components of DM separated by a small mass splitting of order $\delta \sim \sim 100$ keV, $B_\mu$ and $\epsilon_\mu$ are the hypercharge and $U(1)_d$ gauge fields, and $\epsilon$ parameterizes the size of the kinetic mixing. The mass splitting can be generated by a higher dimension operator $\epsilon$, or radiatively by the breaking of a non-Abelian dark sector gauge symmetry $\epsilon$. Through kinetic mixing, the dark sector photon, $b_\mu$, acquires $\epsilon$-suppressed couplings to quarks and thereby mediates inelastic scattering between DM and nuclei. This scattering will take place along with the elastic scattering described before, realizing a scenario we term semielastic scattering.

Phenomenologically, semielastic DM can be parameterized by the parameters, $m_{\chi_0, \delta, \sigma_E, \sigma_I}$. The elastic scattering ($\sigma_E$) dominates at low nuclear recoil energy while the inelastic scattering ($\sigma_I$) dominates at higher recoil energy. Examples of such a spectrum are shown in Fig. 1. The unique spectral shape changes the constraints and reach, in the $(\sigma_E, m_{\chi_0})$ plane, as shown in Fig. 2. We do not attempt to fit the possible DAMA signal.

III. MODEL

We now provide an explicit realization of the scenario described above. We take as our starting point the NMSSM, where a singlet superfield $S$ couples to the two Higgs multiplets of the MSSM. To this, we add an additional coupling of the singlet to DM, as in Eq. 1 and a $U(1)_d$ dark sector along the lines of Refs. 6, 13.

In detail, we will be concerned with the following terms in the superpotential,

$$W \supset \lambda S H_u \cdot H_u + \eta S \chi \chi + \frac{1}{3} \kappa S^3 + \rho N R \bar{R} + \frac{1}{\Lambda} \chi^2 \bar{R}^2$$

(3)

where $H_u$ and $H_u$ are the two Higgs doublet fields, $S$ is the NMSSM singlet, $\chi$ and $\chi$ will compose our DM candidate, $R$ and $\bar{R}$ are GeV-scale dark sector Higgs fields, and $N$ is a GeV-scale singlet whose presence insures that all dark sector fields receive a tree-level mass $\bar{\Lambda}$. We will see below that the higher-dimension operator, suppressed by $\Lambda \gtrsim 10$ TeV, will generate a small DM mass splitting.

We assign $\chi$ and $R$ ($\bar{\chi}$ and $\bar{R}$) charge 1 (-1) under a dark $U(1)_d$ gauge group. Furthermore, we assume the presence of supersymmetric kinetic mixing,

$$\mathcal{L} \supset -\frac{\epsilon}{2} \int d^2 \theta W_Y W_Y,$$

(4)

for $W_Y$ and $W_\eta$, the hypercharge and dark supersymmetric field strengths, where $\epsilon \sim 10^{-4} \sim 10^{-5}$ is naturally generated, at one loop, by integrating out physics at higher energy scales. Expanding in components, the kinetic mixing includes D-term mixing, which generates an effective Fayet-Iliopoulos D-term in the hidden sector at the GeV scale.

Upon minimizing the dark sector potential one finds that $R_e$ develops a VEV $\langle R_e \rangle \equiv v_e \sim \text{GeV}$ which Higgses the dark photon, giving it a mass $m_{\gamma_d} = g_d v_e$. The other light dark sector states also live at the GeV-scale. Finally, we note that there can be $O(1)$ corrections to their masses coming from SM SUSY breaking, which is communicated to the dark sector through gauge interactions with $\chi$ acting as a messenger. These corrections have been included in our benchmark spectra of section IV, although they have no qualitative effect on the phenomenology.

We now consider the spectrum of the $\chi$ multiplet, which will contain DM. After $S$ gets a VEV, there are two nearly degenerate fermionic states with masses $\sim v_e/\sqrt{2}$ (these states are split a small amount by the higher-dimension operator). Meanwhile, the scalar components are split from their supersymmetric masses by

FIG. 2: The left panel shows the current 90% limits, from CDMS $^{14}$ and XENON100 $^{15}$, on the semielastic scenario in the DM mass - elastic cross-section plane. We have fixed the DM splitting, $\delta = 140$ keV, and inelastic cross-section, $\sigma_I = 1.7 \times 10^{-40}$ cm$^2$ per proton, to match the second benchmark of Section IV. We have also included the projected limit from XENON100 after one year of data, assuming zero background, a raw exposure of 6000 kg$\times$days, an efficiency of 38%, and a nuclear recoil energy range of 8.7 to 40 keV. The prominent dip in cross-section indicates the range of masses where the model will be visible from inelastic scattering alone (the dashed orange curve shows the limit without inelastic scattering). This can be seen on the right panel which shows the current and projected limits on inelastic scattering only, with $\delta = 140$ keV. The black (dashed) horizontal line on the right corresponds to the inelastic cross-section assumed on the left.
\( \langle F_S \rangle \), and under the assumption that \( \chi \)'s dominant source of SUSY breaking is communicated by \( S \), we can neglect additional soft terms. The four scalar degrees of freedom divide into two pairs with masses above and below the fermions, separated by a large weak-scale splitting, 

\[
m^2 = \eta \left[ \frac{v_s^2}{2} (\eta \pm \kappa) \mp \frac{\lambda}{4} v_{EW}^2 \sin(2\beta) \right],
\]

where \( v_s \) is the singlet VEV. Within each scalar pair there is a smaller splitting

\[
\delta m^2 = \sqrt{2} n v_s^2 \frac{\eta^2}{\Lambda}
\]

where \( \eta \) is the VEV of the dark Higgs. In what follows, we will label the scalar mass eigenstates \( \chi_i \) for \( i : 0 \to 3 \) in order of ascending mass. The lightest state, \( \chi_0 \), will serve as our DM candidate, and \( \delta m = m_{\chi_i} - m_{\chi_0} \approx 100 \text{ keV} \) is a consequence of Eq. (3).

Now, demanding that this model reproduce the observed relic abundance of dark matter places strong constraints on the different couplings and VEVs. DM can annihilate via three competitive channels: (1) to Higgses and singlets, (2) via dark sector gauge interactions, and (3) to dark sector Higgses through the higher-dimension contact interaction of Eq. (3). DM has the observed relic abundance of dark matter places strong constraints on the different couplings and VEVs. DM can annihilate through dark sector gauge interactions with rate,

\[
\langle \sigma v \rangle \sim \frac{g_d^4}{8\pi m_{\chi_0}^2}
\]

which constrains the dark gauge coupling:

\[
\left( \frac{g_d}{0.5} \right)^2 \left( \frac{1 \text{ TeV}}{m_{\chi_0}} \right)^2 \lesssim 1
\]

In addition, the non-renormalizable operator that generates the small DM splitting allows DM to annihilate into pairs of dark-Higgses,

\[
\langle \sigma v \rangle \sim \frac{(\delta m_{\chi_0})^2}{8\pi v_s^4}. \tag{13}
\]

Therefore, we find a non-trivial constraint relating the mass splitting between the dark matter states and the dark sector breaking scale [8],

\[
\left( \frac{\delta m_{\chi_0}}{100 \text{ keV}} \right)^2 \left( \frac{1 \text{ GeV}}{v_s} \right)^2 \lesssim 1 \tag{14}
\]

We conclude this section with a brief discussion of other important constraints on this model. We note that the excited state \( \chi_1 \) is long-lived and has a relic density that is constrained by inelastic down-scattering, but its density can be depleted in several ways as discussed by Ref. [20]. There are a number of additional constraints if one attempts to explain the cosmic ray anomalies through Sommerfeld enhanced annihilations as in Refs. [2, 4]. Dark matter can annihilate into hidden sector gauginos which decay to a dangerous amount of SM photons as discussed by [8]. This constraint is alleviated if \( m_{\text{gravitino}} \gtrsim 1 \text{ GeV} \), or by considering a more elaborate dark sector. There is tension from astrophysical limits on neutrinos and photons from final state radiation, coming from the galactic center [21]. Alternatively, these astrophysical tensions are alleviated if the cosmic rays are produced by DM decays into the dark sector [8].

**IV. BENCHMARKS**

It is convenient to consider this model in the various analytically tractable limits of the NMSSM. One finds, however, that whether one starts with a small \( \kappa \) (the PQ-symmetric limit [22]) or with small \( A \)-terms (the R-symmetric limit [23]), the requirement of a sizable \( v_s \), a stable EWSB minima, and an elastic recoil spectra visible at current direct detection experiments necessitates small \( \kappa \) and \( \lambda \). We therefore consider the limit \( \kappa, \lambda \to 0 \).

DM scatters elastically by exchanging the three CP-even Higgses, \( s, h, \) and \( H \). With DM at the TeV scale and the three scalar Higgs masses above 100 GeV, we find that it will be difficult to see the elastic scattering at current direct detection experiments. Things become
more interesting if one of these states is light, enhancing the elastic cross-section. The mostly-singlet scalar, $s$, enjoys suppressed couplings to the electroweak gauge bosons and can be very light without conflicting with existing LEP limits [24]. We work in the limit where $m_s \lesssim 50$ GeV. One finds

$$\sigma_{\text{el}} \sim 1.7 \times 10^{-40} \text{ cm}^2 \left( \frac{m_{\chi_0}}{v_s} \right)^2 \left( g_H^2 \frac{g_{\alpha H}}{g_{h \alpha H}} + \frac{g_h^2}{m_s^2} \right)^2$$

where $g_h \sim 1$ and $g_H \sim \frac{1}{2} (\tan \beta - \cot \beta)$ parameterize the couplings of $h$ and $H$ to nucleons [25] (we use the nuclear matrix elements of Ref. [26]), and $\alpha_h/\alpha_H$ denote the singlet-Higgs mixing angles. Note that while it seems one can arbitrarily increase $\sigma_E$ via $g_H$ by choosing a large $\tan \beta$, the singlet proportionally decouples from $H$, so no such tuning is possible.

We present 2 benchmark points in Table I. Both yield the correct relic abundance and a recoil spectrum visible in one year of XENON100 data.

**V. DISCUSSION**

Here we have studied a mechanism that naturally relates the mass of DM to the scale of electroweak symmetry breaking in models with a GeV-scale dark sector. DM scatters against nuclei elastically via a Higgs/singlet, and inelastically through dark gauge boson exchange. Combined, the spectrum has a unique semielastic shape which can be discovered in upcoming direct detection experiments such as XENON100.

While our primary concern has been the unique recoil spectrum particular to this class of models, we found in Sec. III that the parameters are constrained, nontrivially, by the requirement of getting the right relic density. It would be interesting to further investigate the interplay between these constraints and the modified Higgs phenomenology of the NMSSM.

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**TABLE I: Benchmark points for semielastic scattering.** Here $m_\chi$ is the mass of the lightest CP-even scalar, which tends to dominate the elastic scattering rate. The first benchmark has a DM mass that can explain the cosmic ray anomalies with annihilations ($m_{\chi_0} \sim 1$ TeV), while the second benchmark has a mass appropriate for decaying DM ($m_{\chi_0} \sim 2$ TeV) [21].

| $\lambda$ | $\eta$ | $\kappa$ | $\tan \beta$ | $\lambda_\chi$ | $\lambda_\Lambda$ | $v_s$ | $g_\alpha$ | $\epsilon$ | $m_{\chi_0}$ | $\delta m_\chi$ | $m_\nu$ | $\sigma_\gamma$ (per nucleon) | $\sigma_t$ (per proton) |
|---------|--------|----------|-------------|----------------|----------------|------|--------|------|-------------|--------------|--------|-------------------|---------------------|
| 0.025   | 0.20   | 0.0060   | 15          | −110 GeV      | 300 GeV        | 7 TeV | 0.5    | 2 × 10^{-4} | 975 GeV      | 203 keV      | 14 GeV | 1.7 × 10^{-43} cm^2 | 8.3 × 10^{-39} cm^2 |
| 0.015   | 0.40   | 0.0015   | 10          | −15 GeV       | 20 GeV         | 8 TeV | 0.6    | 3 × 10^{-5} | 2259 GeV     | 140 keV      | 12 GeV | 4.3 × 10^{-43} cm^2 | 1.7 × 10^{-40} cm^2 |

[1] O. Adriani et al., Nature **458**, 607 (2009), 0810.4995. F. Aharonian et al., Phys. Rev. Lett. **101**, 261104 (2008), 0811.3894. F. Aharonian et al., Astron. Astrophys. **508**, 561 (2009), 0905.0105. A. A. Abdo et al., Phys. Rev. Lett. **102**, 181101 (2009), 0905.0025.
[2] N. Arkani-Hamed et al., Phys. Rev. D **79**, 015014 (2009), 0810.0713.
[3] N. Arkani-Hamed and N. Weiner, JHEP **0812**, 104 (2008), 0810.0714.
[4] M. Pospelov et al., Phys. Lett. B **662**, 53 (2008), 0711.4866. Y. Nomura and J. Thaler, Phys. Rev. D **79**, 075008 (2009), 0810.5397.
[5] M. Baunsgard et al., JHEP **0904**, 014 (2009), 0901.0283.
[6] C. Cheung et al., Phys. Rev. D **80**, 035008 (2009), 0902.3246.
[7] X. Chen, JCAP **0909**, 029 (2009), 0902.0008. J. Mardon et al., Phys. Rev. D **80**, 035013 (2009), 0905.3749.
[8] J. T. Ruderman and T. Volansky, JHEP **1002**, 024 (2010), 0908.1570. J. T. Ruderman and T. Volansky, arXiv: 0907.4373.
[9] D. Tucker-Smith and N. Weiner, Phys. Rev. D **64**, 043502 (2001), hep-ph/0101138. D. Tucker-Smith and N. Weiner, Phys. Rev. D **72**, 063509 (2005), 0402065. S. Chang et al., Phys. Rev. D **79**, 043513 (2009), 0807.2250.
[10] R. Bernabei et al., Eur. Phys. J. C **67**, 39 (2010), 1002.1028.
[11] J. March-Russell et al., JHEP **0807**, 058 (2008), 0801.3440. D. E. Kaplan et al., Phys. Rev. D **79**, 115016 (2009), 0901.4117.
[12] R. H. Helm, Phys. Rev. **104**, 1466 (1956).
[13] J. D. Lewin and P. F. Smith, Astropart. Phys. **6**, 87 (1996).
[14] D. S. Akerib et al. Phys. Rev. Lett. **93**, 211301 (2004), astro-ph/0405033. D. S. Akerib et al. Phys. Rev. Lett. **96**, 011302 (2006), astro-ph/0509259. Z. Ahmed et al. Phys. Rev. Lett. **102**, 011301 (2009), 0802.3530. Z. Ahmed et
al., arXiv:0912.3592.
[15] E. Aprile et al., arXiv:1005.0380.
[16] H. P. Nilles et al., Phys. Lett. B 124, 337 (1983).
  J. M. Frere et al., Nucl. Phys. B 222, 11 (1983).
  J. P. Derendinger and C. A. Savoy, Nucl. Phys. B 237, 307 (1984).
[17] M. Lisanti and J. G. Wacker, arXiv:0911.4483.
[18] A. Katz and R. Sundrum, JHEP 0906, 003 (2009), 0902.3271.
  D. E. Morrissey et al., JHEP 0907, 050 (2009), 0904.2567.
[19] J. L. Feng et al., 1005.4678. M. R. Buckley and P. J. Fox,
  Phys. Rev. D 81, 083522 (2010), 0911.3898.
[20] D. P. Finkbeiner et al., JCAP 0909, 037 (2009), 0903.1037.
[21] P. Meade et al., Nucl. Phys. B 831, 178 (2010), 0905.0480.
[22] L. J. Hall and T. Watari, Phys. Rev. D 70, 115001 (2004), hep-ph/0405109.
[23] B. A. Dobrescu and K. T. Matchev, JHEP 0009, 031 (2000), hep-ph/0008192.
[24] R. Barate et al. Phys. Lett. B 565, 61 (2003), hep-ex/0306033.
[25] X. G. He et al., Phys. Rev. D 79, 023521 (2009), 0811.0658.
[26] J. Giedt et al., Phys. Rev. Lett. 103, 201802 (2009), 0907.4177.
[27] For a different model that includes inelastic scattering with a subdominant component of elastic scattering, we refer the reader to Ref. [17].