FERMILAB-PUB-10-316-A

CoGeNT, DAMA, and Light Neutralino Dark Matter

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Recent observations by the CoGeNT collaboration (as well as long standing observations by DAMA/LIBRA) suggest the presence of a $\sim$ 5-10 GeV dark matter particle with a somewhat large elastic scattering cross section with nucleons ($\sigma \sim 2\times10^{-40}$ cm^2). Within the context of the minimal supersymmetric Standard Model (MSSM), neutralinos in this mass range are not able to possess such large cross sections, and would be overproduced in the early universe. Simple extensions of the MSSM, however, can easily accommodate these observations. In particular, the extension of the MSSM by a chiral singlet superfield allows for the possibility that the dark matter is made up of a light singlino that interacts largely through the exchange of a fairly light ($\sim$30-70 GeV) singlet-like scalar Higgs. Such a scenario is consistent with all current collider constraints and can generate the signals reported by CoGeNT and DAMA/LIBRA. Furthermore, the thermal relic abundance in this scenario is naturally close to the measured density of dark matter.

PACS numbers: 95.35.+d, 12.60.Jv, 14.80.Da; FERMILAB-PUB-10-316-A; UCI-HEP-TR-2010-17; UCD-HEP-TH-2010-12

arXiv:1009.0549v1 [hep-ph] 2 Sep 2010

Recently, the CoGeNT collaboration has reported the detection of very low energy events which cannot be accounted for with known backgrounds [1]. It has been shown than it is possible to interpret these events as the elastic scattering of a light dark matter particle ($m \sim 5-10$ GeV) with a cross section on the order of $\sim10^{-40}$ cm^2 [1–3]. Intriguingly, the range of masses and cross sections implied by CoGeNT is not very far from the region required to explain the annual modulation observed by the DAMA/LIBRA collaboration [4].

Since the announcement of the CoGeNT result, a number of groups have begun to explore the dark matter phenomenology of this signal [3, 5]. Within the context of the Minimal Supersymmetric Standard Model (MSSM), dark matter explanations for the CoGeNT/DAMA signals face considerable challenges. The range of elastic scattering cross sections predicted for neutralinos falls more than an order of magnitude short, even in the most optimal regions of parameter space [6, 7]. While this could plausibly be reconciled by adopting a significantly higher local density of dark matter, the relic abundance of very light (5-10 GeV) neutralinos in the MSSM is also predicted to be well above the measured cosmological dark matter density [7, 8]. Thus, even in optimistic regions of the MSSM parameter space, it is very difficult to accommodate the observations of CoGeNT and DAMA/LIBRA.

To increase the elastic scattering cross section and reduce the thermal relic abundance of neutralino dark matter requires a combination of larger couplings and/or lower masses for the particles exchanged than is possible for very light neutralinos in the MSSM context. In the MSSM, the cross section is dominated by the exchange of scalar Higgs bosons whose masses must lie above $\geq$ 100 GeV due to LEPII and Tevatron constraints. However, the latter constraints need not apply in supersymmetric models with extended Higgs sectors [9]. As we will show, in such scenarios it is possible for a 5-10 GeV neutralino to produce the observed signal through the exchange of a light ($\sim$30-70 GeV) scalar Higgs, while also generating the correct thermal relic abundance.

Generically, the spin-independent elastic scattering cross section of dark matter with a nucleus is written:

$$\sigma \approx \frac{4m_{\rm DM}^2 m_N^2}{\pi(m_{\rm DM}+m_N)^2}[Zf_p + (A-Z)f_n]^2, \qquad (1)$$

where m_N is the mass of the target nucleus (of atomic number Z and mass A), and $m_{\rm DM}$ is the dark matter mass. f_p and f_n are the dark matter's couplings to protons and neutrons:

$$f_{p,n} = \sum_{q=u,d,s} f_{T_q}^{(p,n)} a_q \frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG}^{(p,n)} \sum_{q=c,b,t} a_q \frac{m_{p,n}}{m_q}, \qquad (2)$$

where a_q are the dark matter's couplings to quarks and $f_{T_q}^{(p,n)}$, $f_{TG}^{(p,n)}$ are hadronic matrix elements [10]. A nuclear form factor corrects for finite momentum transfer.

For light MSSM neutralinos, the neutralino-quark coupling is dominated by scalar Higgs exchange (contributions from squark exchange are typically negligible). For down-type quarks, this coupling is [11]:

$$\begin{aligned}\frac{a_d}{m_d} &= \frac{g_2}{4m_W\cos\beta}[-g_1N_{11}+g_2N_{12}] \qquad (3)\\ &\times \left[\left(\frac{N_{13}c_\alpha^2 - N_{14}c_\alpha s_\alpha)}{m_{H^0}^2}\right) + \left(\frac{N_{13}s_\alpha^2 + N_{14}c_\alpha s_\alpha)}{m_{h^0}^2}\right)\right],\end{aligned}$$

where the N_{1i}'s denote the composition of the lightest neutralino ($\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$), and s_α and c_α denote the sine and cosine of α, which relate the scalar mass and gauge eigenstates. The corresponding expression for up-type quarks is found by replacing $\cos\beta \leftrightarrow \sin\beta$ and $N_{14} \leftrightarrow N_{13}$.

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

The largest elastic scattering cross sections in the MSSM arise in the case of large $\tan\beta$ and $\sin(\beta-\alpha)\sim 1$, significant N_{13}, and relatively light m_{H^0}. In this limit, the lighter Higgs, h^0, is approximately Standard Model-like and the heavier H^0 is approximately H_d^0, and one finds $\frac{a_d}{m_d}\approx\frac{-g_2 g_1 N_{13}N_{11}\tan\beta\, c_\alpha^2}{4m_W m_{H^0}^2}$, which yields $\sigma_{\chi_1^0 p,n}\approx$

$$1.7\times 10^{-41}\mathrm{cm}^2\left(\frac{N_{13}^2}{0.103}\right)\left(\frac{\tan\beta}{50}\right)^2\left(\frac{100\,\mathrm{GeV}}{m_{H^0}}\right)^4\left(\frac{c_\alpha}{1}\right)^4. \quad (4)$$

The higgsino content of the lightest neutralino is constrained by the invisible width of the Z as measured at LEP, $\Gamma_{\rm inv}^{\rm LEP}=499\pm 1.5$ MeV. In contrast, the Standard Model prediction for this quantity is slightly (1.4σ) higher, $\Gamma_{\rm inv}^{\rm SM}=501.3\pm 0.6$ MeV [12]. Combining the measured and predicted values, we find a 2σ upper limit of $\Gamma_{Z\to\chi_1^0\chi_1^0}<1.9$ MeV. As $\Gamma_{Z\to\chi_1^0\chi_1^0}$ scales with $[N_{13}^2-N_{14}^2]^2$, we can translate this result to a limit of $|N_{13}^2-N_{14}^2|<0.103$. For moderately large values of $\tan\beta$, the two higgsino terms do not efficiently cancel, requiring $|N_{13}|^2<0.103$.

m_{H^0} and $\tan\beta$ are constrained by a number of measurements, including those of the rare decays $t\to bH^+$, $B_s\to\mu^+\mu^-$, $B^\pm\to\tau\nu$, $b\to s\gamma$, and direct limits on Higgs production followed by $A/H\to\tau^+\tau^-$. While these limits vary somewhat depending on the precise values of the MSSM parameters adopted, in general they imply $\tan\beta\lesssim 30-45$ for $m_{H^0},m_{A^0}\sim 90-150$ GeV. Constraints from LEP II further require $m_{H^0,A^0,H^\pm}\gtrsim 90$ GeV. When these limits are taken into account, we find that $\sigma_{\chi_1^0 p,n}\lesssim 10^{-41}$ cm^2 [6, 7], which falls short of that implied by the CoGeNT and DAMA/LIBRA signal by about an order of magnitude. Furthermore, light neutralinos in the MSSM are inevitably predicted to freeze out with a thermal relic abundance in excess of the measured dark matter density.

To increase the cross section beyond the range allowed in the MSSM, an obvious direction is to consider models with lighter Higgs bosons. As the cross section scales with the inverse of the fourth power of the exchanged Higgs mass, even modest reductions could increase the cross section to the levels required. As an example of a framework in which light Higgs bosons are possible, we extend the MSSM by a chiral singlet superfield $\hat{S}$, containing two neutral scalars H_S^0 and A_S^0 and a Majorana fermion $\tilde{S}$. The theory is described by superpotential [13]

$$\frac{1}{2}\mu_S\hat{S}^2+\mu\hat{H}_u\hat{H}_d+\lambda\hat{S}\hat{H}_u\hat{H}_d+\frac{1}{3}\kappa\hat{S}^3\ , \quad (5)$$

(along with the MSSM Yukawa interactions) and soft Lagrangian

$$\begin{aligned}-\mathcal{L}_{soft} &= v_S^3 S+B_\mu H_u H_d+\frac{1}{2}m_S^2|S|^2+\frac{1}{2}B_S S^2\\ &\quad+\lambda A_\lambda S H_u H_d+\frac{1}{3}\kappa A_\kappa S^3+H.c. \quad (6)\end{aligned}$$

(along with the MSSM A-terms). Specific implementations of such a singlet typically involve a subset of these terms. For example, in the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [14], a Z_3 symmetry is imposed which only allows the terms involving λ, κ, A_λ and A_κ. Here, we do not tie ourselves to this particular model, but instead consider the full range of terms as described in Eqs. (5) and (6).

The tree-level neutralino mass matrix in the $\tilde{B},\tilde{W}^3,\tilde{H}_u,\tilde{H}_d,\tilde{S}$ basis is

$$\mathcal{M}_{\tilde{\chi}^0}=\begin{pmatrix} M_1 & 0 & \frac{g_1 v_u}{\sqrt{2}} & -\frac{g_1 v_d}{\sqrt{2}} & 0\\ 0 & M_2 & -\frac{g_2 v_u}{\sqrt{2}} & \frac{g_2 v_d}{\sqrt{2}} & 0\\ \frac{g_1 v_u}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 & -\mu-\lambda s & -\lambda v_d\\ -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_2 v_d}{\sqrt{2}} & -\mu-\lambda s & 0 & -\lambda v_u\\ 0 & 0 & -\lambda v_d & -\lambda v_u & 2\kappa s+\mu_S\end{pmatrix}, \quad (7)$$

where v_u and v_d are the up- and down-type Higgs vevs and s is the vev of the singlet Higgs. A light ($\lesssim 10$ GeV) neutralino consistent with LEP II chargino searches must be either mostly $\tilde{B}$ or $\tilde{S}$. The $\tilde{B}$ does not couple to a mostly singlet Higgs, and that case is thus similar to the MSSM. From here on, we focus on the case where the lightest neutralino is mostly $\tilde{S}$. One might imagine that the strict NMSSM would allow sufficient flexibility. However, in a companion paper [15], we show that after imposing LEP and B-physics constraints the lightest neutralino *is* always bino-like and elastic cross sections as large as required by CoGeNT and DAMA/LIBRA are not possible in the NMSSM. Nonetheless they are "only" a factor of 10 too small (whereas in Ref. [16] the largest cross section found was a factor of 100 too small).

We proceed by engineering the lightest neutralino to be mostly $\tilde{S}$, together with a light Higgs that is predominantly singlet. The lightest neutralino will naturally be predominantly singlino provided the quantity $|2\kappa s+\mu_S|$ is much smaller than $|\mu+\lambda s|$, M_1 and M_2. For example, for $\kappa=0.6$, $s=6$ GeV, $\mu_S\approx 0$, $\lambda=0.1$, large $\tan\beta$, large M_1, large M_2, and μ =150 GeV, we find that the lightest neutralino is singlino-like ($N_{15}^2=0.974$) with a mass of approximately 7.2 GeV.

The conditions under which the lightest Higgs, h_1, is mostly singlet are somewhat more complicated. A simple limit which leads to desired phenomena can be obtained for small λ. In the limit $\lambda\to 0$, the singlet decouples from the MSSM (which has standard Higgses), and has a mass determined by B_S, m_S^2, μ_S, κ, s, and A_κ. Thus, provided the soft terms for the singlet are sufficiently small, and λv is much smaller than m_h, the singlet represents a perturbation on MSSM Higgs phenomenology, with a light singlet state mixed with the MSSM to a degree controlled by λ. In this limit, the light CP odd Higgs will also be predominantly singlet. Through mixing with the MSSM Higgses, both the light CP even and CP odd states have couplings proportional to the usual MSSM interactions, but reduced by the small amount of mixing.

The singlino coupling to down-type quarks is given by:

$$\frac{a_d}{m_d}=\frac{g_2\kappa N_{15}^2\tan\beta F_s F_d}{8m_W m_{h_1}^2} \quad (8)$$

where $h_1 = F_d H_d^0 + F_u H_u^0 + F_s H_S^0$. This leads to

$$\sigma_{\chi_1^0 p,n} \approx 2.2 \times 10^{-40}\,\mathrm{cm}^2 \times \left(\frac{\kappa}{0.6}\right)^2 \left(\frac{\tan\beta}{50}\right)^2 \left(\frac{45\,\mathrm{GeV}}{m_{h_1}}\right)^4 \left(\frac{F_s^2}{0.85}\right)\left(\frac{F_d^2}{0.15}\right), \quad (9)$$

which is consistent with the value required by CoGeNT and DAMA/LIBRA. Furthermore, the mostly singlet nature ($F_s^2 = 0.85$) of the h_1 easily allows it to evade the constraints from LEP II and the Tevatron, as we discuss below. The fact that moderately large F_d is required argues that this scenario will be difficult to arrange in the (MSSM) decoupling regime of $m_{a_2}, m_{h_3} \gg m_{h_2}$, implying that all of the mostly MSSM Higgses are likely to have masses only slightly above the LEP II limit.

Collider constraints on the h_1 are largely evaded for sufficiently large F_s. LEP II places constraints through production of Zh_i (for the scalars) and pair production of $a_i h_j$ for the pseudoscalars. The heavier mass eigenstates (h_2, h_3, and a_2) look like their MSSM counterparts, with their couplings slightly reduced by the small singlet component. Thus, provided they represent a viable point of MSSM parameter space, they will be allowed here as well. The light (mostly singlet) h_1 and a_1 must have small enough Z-Z-h_1 and Z-h_i-a_1 interactions to be consistent with existing searches. Zh_1 production at LEP II requires the SM-like Higgs fraction of h_1 (for large $\tan\beta$, roughly F_u) to be < 0.2 for $m_{h_1} \sim 50$ GeV [17]. Evading this bound thus depends on arranging $F_u \lesssim F_d \ll F_s$ which can be accomplished in the limit $A_\lambda \gtrsim \mu$. If the pseudoscalar, a_1, has a similar doublet fraction, this level of mixing is also permitted by $h_1 a_1$ pair production provided $m_{a_1} + m_{h_1} \gtrsim 100$ GeV. Pair production of a_1 together with the mostly SM-like light Higgs h_2 allows a_1 to have a doublet fraction of 0.2 provided $m_{h_2} + m_{a_1} \gtrsim 160$ GeV. The Tevatron can produce pseudoscalars through the reaction $bg \to ba_1$, where a_1 can decay into either $b\bar{b}$ or $\tau^+\tau^-$ pairs. Null Tevatron searches require $\tan\beta \lesssim 50$ for a doublet-like pseudoscalar with mass of order 100 GeV [18], but this limit is significantly weakened in the case of a mostly singlet a_1. A similar limit on $\tan\beta$ can be obtained from the null search for $t \to H^+ b$ [19]. Much of this scenario can be tested by end-phase Tevatron or early LHC running.

The thermal relic density of neutralinos is determined by the annihilation cross section and mass. In the mass range we are considering here, the dominant annihilation channel is to $b\bar{b}$ (or, to a lesser extent, to $\tau^+\tau^-$) through the s-channel exchange of a Higgs boson. In particular, the annihilation cross section that results from s-channel exchange of the *same* scalar Higgs, h_1, as employed for elastic scattering is:

$$\sigma_{\chi_1^0\chi_1^0} v = \frac{N_c g_2^2 \kappa^2 m_b^2 F_s^2 F_d^2}{64\pi m_W^2 \cos^2\beta} \frac{m_{\chi_1^0}^2 (1 - m_b^2/m_{\chi_1^0}^2)^{3/2}\, v^2}{(4m_{\chi_1^0}^2 - m_{h_1}^2)^2 + m_{h_1}^2 \Gamma_{h_1}^2}, \quad (10)$$

where v is relative velocity between the annihilating neutralinos, $N_c = 3$ is a color factor and Γ_{h_1} is the width of the exchanged Higgs. The annihilation cross section into $\tau^+\tau^-$ is obtained by replacing $m_b \to m_\tau$ and $N_c \to 1$. This yields the thermal relic abundance of neutralinos: $\Omega_{\chi_1^0} h^2 \approx \frac{10^9}{M_{\mathrm{Pl}}} \frac{m_{\chi_1^0}}{T_{\mathrm{FO}}\sqrt{g_\star}} \frac{1}{\langle \sigma_{\chi_1^0\chi_1^0} v\rangle}$, where $g_\star$ is the number of relativistic degrees of freedom at freeze-out, $\langle \sigma_{\chi_1^0\chi_1^0} v\rangle$ is the thermally averaged annihilation cross section at freeze-out, and T_{FO} is the temperature at which freeze-out occurs. For the range of masses and cross sections considered here, we find $m_{\chi_1^0}/T_{\mathrm{FO}} \approx 20$, yielding a thermal relic abundance of

$$\Omega_{\chi_1^0} h^2 \approx 0.11 \left(\frac{0.6}{\kappa}\right)^2 \left(\frac{50}{\tan\beta}\right)^2 \left(\frac{m_{h_1}}{45\,\mathrm{GeV}}\right)^4 \times \left(\frac{7\,\mathrm{GeV}}{m_{\chi_1^0}}\right)^2 \left(\frac{0.85}{F_s^2}\right)\left(\frac{0.15}{F_d^2}\right), \quad (11)$$

which is approximately equal to the measured dark matter density, $\Omega_{\mathrm{CDM}} h^2 = 0.1131 \pm 0.0042$ [23].

Using parameter regions guided by the above discussions, we performed parameter scans with an extended version of NMHDECAY [20] and micrOmegas [21] that includes both the non-NMSSM parameters of Eqs. (5) and (6) as well as the latest B-physics and Tevatron constraints. We find points for $15 < \tan\beta < 45$ that are consistent (within 2σ) with all collider and B-physics constraints (aside from $\sim 2.5\sigma$ excursions in $b \to s\gamma$ and $b\bar{b}h, h \to \tau^+\tau^-$) having the appropriate thermal relic density and large $\sigma_{\chi_1^0 p,n} \sim 10^{-40} - 10^{-39}\mathrm{cm}^2$. The complete framework has contributions to $\sigma_{\chi_1^0 p,n}$ and $\Omega_{\chi_1^0}$ beyond Eqs. (9) and (11) and high-$\sigma_{\chi_1^0 p,n}$ points typically have large contributions from the non-singlet Higgses. More details will appear in [22].

Despite the velocity suppressed annihilation cross section for scalar Higgs exchange, not only can an acceptable thermal relic abundance be easily accommodated, but the desired relic density is natural once the relevant combination of couplings and Higgs mass are set to accommodate CoGeNT and DAMA/LIBRA. This general conclusion applies to any Majorana fermion dark matter which couples to Standard Model quarks through a (non-resonant) scalar. This confluence of parameter space is peculiar to models with a scalar exchange [2, 24, 25]. For example, a Dirac fermion or a scalar with vector interactions will either overproduce the CoGeNT and DAMA/LIBRA rates or will predict a thermal relic density in excess of the measured value.

This scenario also has interesting implications for the indirect detection of dark matter. In particular, as the dark matter annihilation rate in any given region scales with the inverse of the square of the dark matter mass, the light neutralino we are considering could, in principle, lead to enhanced fluxes of various annihilation products (gamma rays, neutrinos, charged cosmic rays, etc.). At late times, however, the scalar Higgs exchange that dominates neutralino annihilation in the early universe is suppressed by the low dark matter velocities. As a result, other annihilation processes (such as through pseudoscalar exchange) will likely dominate the rate in the

current universe. Furthermore, due to its light mass and large elastic scattering cross section, the neutralino in this scenario would be captured by and annihilate in the Sun at a very high rate, potentially producing an observable flux of neutrinos in large volume, low-threshold neutrino telescopes [2, 27].

In summary, we have considered in this letter the possibility that neutralino dark matter is responsible for the signals reported by the CoGeNT and DAMA/LIBRA collaborations. Although, the elastic scattering cross section of neutralinos with nuclei in the MSSM is too small to account for these observations, the same conclusion is not necessarily reached in extended supersymmetric models. In particular, we have discussed models in which the MSSM is extended by a chiral singlet superfield. In such a model, a light singlino-like neutralino, which interacts with nuclei through the exchange of a largely singlet-like, scalar Higgs, can possess an elastic scattering cross section capable of generating the observations reported by CoGeNT and DAMA/ LIBRA. Furthermore, such a scenario more or less automatically leads to a thermal relic abundance of neutralinos induced by annihilation through the same Higgs that is roughly consistent with the observed relic density.

Acknowledgements

AB and DH are supported by the US Department of Energy, including grant DE-FG02-95ER40896, and by NASA grant NAG5-10842. JFG is supported by US DOE grant DE-FG03-91ER40674. TT is supported by NSF grant PHY-0970171. JFG, DH, and TMPT acknowledge the Aspen Center for Physics, where this project began.

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