Singlet fermionic dark matter explains DAMA signal

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ABSTRACT: It has been suggested that, considering channeling effect, the order of a few GeV dark matters which are elastically scattered from detector nuclei might be plausible candidates reconciling the DAMA annual modulation signal with the results of other null experiments. We show that Singlet Fermionic Dark Matter can be such a dark matter candidate, simultaneously providing the correct thermal relic density which is consistent with the WMAP data.

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Contents

1 Introduction

We have now compelling evidences for the existence of non-baryonic dark matter (DM) in the universe, whose mass density has been accurately measured by the Wilkinson Microwave Anisotropy Probe (WMAP) [1]. The DM mass density normalized by the critical density is given by, in the 3σ range,

$$0.091 < \Omega_{\rm CDM}h^2 < 0.129, \tag{1.1}$$

where $h \approx 0.7$ is the scaled Hubble constant in the units of 100 (km/sec)/Mpc.

Recently, the DAMA collaboration has reported the observation of an annual modulation [2] in nuclear recoil rate of NaI(Tl) detectors [3]. The DAMA signal is consistent with elastic, spin independent DM scattering from target nuclei in the detectors. The conventional signal region corresponds to the DM mass and the scattering cross section $(m_{\rm DM}, \sigma_p^{\rm SI}) \sim (30 - 200\,{\rm GeV}, 10^{-5}\,{\rm pb})$, which is now excluded by other DM search experiments such as XENON10 [4] and CDMS (Ge) [5].

It has been shown, however, that considering effect of channeling [6, 7] in the NaI crystal scintillators of DAMA, the spin-independent elastic scattering of DM with nuclei can accommodate the DAMA signal with the results of other null experiments. The corresponding region of the cross section, which might be compatible with all experiments (even without considering dark stream [8]), is given by [7]

$$3 \times 10^{-41}{\rm cm}^2 \lesssim \sigma_p^{\rm SI} \lesssim 5 \times 10^{-39}{\rm cm}^2, \tag{1.2}$$

with a DM mass in the range of

$$3\,{\rm GeV} \lesssim m_{\rm DM} \lesssim 8\,{\rm GeV}. \tag{1.3}$$

Various models have been studied to accommodate the DAMA signal region with the parameters of (1.2) and (1.3), which include mirror dark matter [9], WIMPless dark matter [10], light neutralino in the minimal supersymmetric standard model (MSSM) [11] and right-handed sneutrino dark matter from Next-to-MSSM (NMSSM) [12]. Adding to

those models, there are other good approaches explaining the DAMA modulation signals as massive WIMPs (heavier than $100\,\mathrm{GeV}$) free from null experimental bounds, which focus on inelastic dark matter with non-standard halo models of DM velocity distribution or various galactic escape velocities [13].

In this work, we would like to direct a spotlight on a singlet fermionic dark matter [14, 15] elastically scattering from target nuclei with (1.2) and (1.3) to explain the DAMA signal reconciling other null experiments, which can also simultaneously satisfy the measured DM mass density (1.1). Our paper is organized as following. In section 2, we briefly review the model of singlet fermionic dark matter. Model parameter regions, which explain the DAMA signal in the low mass region with the correct thermal relic density, are investigated in section 3. Section 4 is the conclusion.

2 Singlet fermionic dark matter model

A standard model (SM) gauge singlet sector, aka "hidden sector", is introduced, which consists of a real scalar field S and a Dirac fermion field ψ [14].[1] The singlet scalar S couples to the SM particles only through the interactions with the SM Higgs boson. The interaction of the singlet DM fermion ψ with the SM particles comes through the interaction of ψ with the singlet scalar S and the mixing of the scalar S with the SM Higgs.

The model Lagrangian is written as

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{hid}} + \mathcal{L}_{\mathrm{int}}, \tag{2.1}$$

where $\mathcal{L}_{\mathrm{SM}}$ stands for the SM Lagrangian and the hidden sector Lagrangian is given by

$$\mathcal{L}_{\mathrm{hid}} = \mathcal{L}_S + \mathcal{L}_\psi - g_S \bar{\psi}\psi S, \tag{2.2}$$

with

$$\mathcal{L}_S = \frac{1}{2} \left(\partial_\mu S\right)\left(\partial^\mu S\right) - \frac{m_0^2}{2} S^2 - \frac{\lambda_3}{3!} S^3 - \frac{\lambda_4}{4!} S^4, \tag{2.3}$$

$$\mathcal{L}_\psi = \bar{\psi}\left(i\slashed{\partial} - m_{\psi_0}\right)\psi. \tag{2.4}$$

The interaction terms between the singlet scalar S and the SM Higgs H are given by

$$\mathcal{L}_{\mathrm{int}} = -\lambda_1 H^\dagger H S - \lambda_2 H^\dagger H S^2. \tag{2.5}$$

The scalar potential given in eq. (2.3) and (2.5), together with the SM Higgs potential

$$V_{\mathrm{SM}} = -\mu^2 H^\dagger H + \lambda_0 (H^\dagger H)^2, \tag{2.6}$$

derives vacuum expectation values, $\langle H^0 \rangle = v_0/\sqrt{2}$ and $\langle S \rangle = x_0$, of the neutral component of the SM Higgs and the singlet scalar, respectively. The extremum conditions

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[1]For other recent studies of hidden dark matter, see refs. [16].

$\partial V/\partial H|_{<H^0>=v_0/\sqrt{2}} = 0$ and $\partial V/\partial S|_{<S>=x_0} = 0$, of total scalar potential V, lead to the following relations among the model parameters [17]

$$\mu^2 = \lambda_0 v_0^2 + (\lambda_1 + \lambda_2 x_0)x_0,$$
$$m_0^2 = -\frac{\lambda_3}{2}x_0 - \frac{\lambda_4}{6}x_0^2 - \frac{\lambda_1 v_0^2}{2x_0} - \lambda_2 v_0^2. \qquad (2.7)$$

The neutral scalar fields h and s defined by $H^0 = (v_0 + h)/\sqrt{2}$ and $S = x_0 + s$ are mixed to yield the mass matrix given by

$$\mu_h^2 \equiv \left.\frac{\partial^2 V}{\partial h^2}\right|_{h=s=0} = 2\lambda_0 v_0^2,$$
$$\mu_s^2 \equiv \left.\frac{\partial^2 V}{\partial s^2}\right|_{h=s=0} = \frac{\lambda_3}{2}x_0 + \frac{\lambda_4}{3}x_0^2 - \frac{\lambda_1 v_0^2}{2x_0},$$
$$\mu_{hs}^2 \equiv \left.\frac{\partial^2 V}{\partial h \partial s}\right|_{h=s=0} = (\lambda_1 + 2\lambda_2 x_0)v_0. \qquad (2.8)$$

The corresponding mass eigenstates h_1 and h_2 are defined by

$$h_1 = \sin\theta \; s + \cos\theta \; h,$$
$$h_2 = \cos\theta \; s - \sin\theta \; h, \qquad (2.9)$$

where the mixing angle θ is given by

$$\tan\theta = \frac{y}{1 + \sqrt{1 + y^2}}, \qquad (2.10)$$

with $y \equiv 2\mu_{hs}^2/(\mu_h^2 - \mu_s^2)$. Then the two Higgs boson masses m_1 and m_2 are given by

$$m_{1,2}^2 = \frac{\mu_h^2 + \mu_s^2}{2} \pm \frac{\mu_h^2 - \mu_s^2}{2}\sqrt{1 + y^2}, \qquad (2.11)$$

where the upper (lower) sign corresponds to $m_1(m_2)$. From the above definition of the mixing angle θ, we get $|\cos\theta| > 1/\sqrt{2}$, hence h_1 is SM Higgs-like while h_2 is singlet-like.

In total, we have eight independent model parameters relevant for DM phenomenology. The six model parameters $\lambda_0, \lambda_1, \lambda_2, \lambda_3, \lambda_4$ and x_0 determine the masses, mixing and self-couplings of the scalar sector. The singlet fermion ψ has mass $m_\psi = m_{\psi_0} + g_S x_0$ as an independent parameter of the model since m_{ψ_0} is just a free model parameter. Finally, the Yukawa coupling g_S measures the interaction of ψ with singlet component of the scalar particles.

3 Numerical analysis

Spin-independent elastic scattering of the fermionic DM ψ with nucleons arises from $t-$channel Higgs exchange diagrams, which is shown in figure 1. For a light dark matter with $m_\psi \simeq 5\,\text{GeV}$, the spin-independent cross section for DM-proton scattering is approximately given by

$$\sigma(\psi p \to \psi p) \sim 0.1 \left(\frac{g_S \cos\theta \sin\theta}{v_0 \, m_{h_2}^2}\right)^2 (\text{GeV}^4), \qquad (3.1)$$
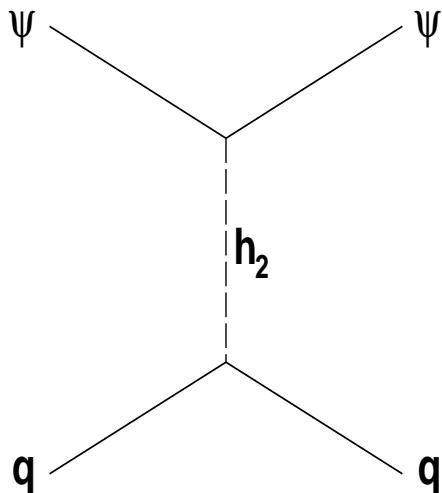
Figure 1. Dominant diagram for spin-independent DM-nucleon scattering, with a low mass of the singlet-like Higgs h_2.

assuming $m_{h_2} \ll m_{h_1}$. With $g_S \sim O(1)$, a low Higgs mass m_{h_2} is needed in order to obtain a desired value of $\sigma(\psi p \to \psi p) \sim 10^{-4}$ pb for explaining the DAMA result. On the other hand the scalar mixing angle $\sin\theta$, which determines ZZh_2 coupling, should be small not to conflict with the LEP constraint on the Higgs mass [18], for such a low Higgs mass. For instance, $m_{h_2} \sim 5\,(15)\,\text{GeV}$, $\sin\theta \sim 0.01\,(0.1)$ with $g_S = 1$ provides the DAMA favored value for the scattering cross section while satisfying the LEP constraint on the Higgs mass.

One concern about the light fermionic DM scenario for explaining the DAMA data is that it usually leads to too large thermal DM relic density to be compatible with the WMAP measurement (1.1), if DM pair annihilation undergoes mainly through s-channel Higgs exchanges [19]. However, when the singlet-like Higgs mass is less than or similar to the DM particle mass, i.e., $m_{h_2} \lesssim m_\psi$, the dominant contribution for the annihilation of DM pair in the early universe arises from $\psi\bar\psi \to h_2 h_2$ process, which is illustrated in figure 2. In this kinematic regime, the singlet-like Higgs does not decay into the DM pair since it is not kinematically allowed, but it decays entirely into the SM particles. The DM pair annihilation to h_2 pair is not suppressed by the small mixing angle θ because $\bar\psi\psi h_2$ coupling is proportional to $\cos\theta$ rather than $\sin\theta$, thus it may provide large enough annihilation cross-section to have a small DM relic density compatible with the WMAP data [20].
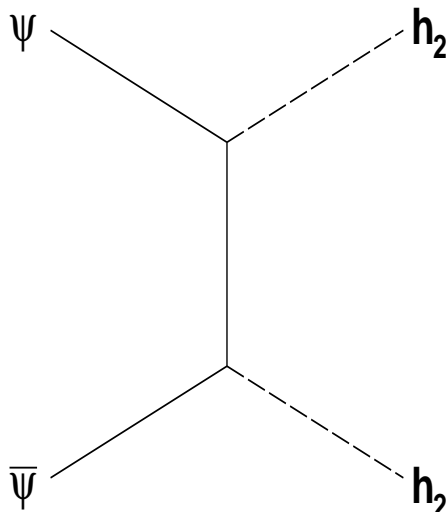
As a specific numerical example, let us consider the following model parameters

$$x_0 = 100\,\text{GeV}, \quad \lambda_0 = 0.12, \quad \lambda_1 = -19, \quad \lambda_2 = 0.1, \quad \lambda_3 = -314\,\text{GeV}, \quad \lambda_4 = 3, \quad (3.2)$$

which provide the masses and mixing angle of two Higgs particles as

$$m_{h_1} = 120.5\,\text{GeV}, \qquad m_{h_2} = 6.7\,\text{GeV} \qquad \text{and } \sin\theta = 0.017. \qquad (3.3)$$

Further setting $m_\psi = 5\,\text{GeV}$ and $g_S = 1.2$, we obtain the following spin-independent DM

Figure 2. Dominant diagram for DM pair annihilation, when $m_\psi \lesssim m_{h_2}$.

scattering cross section and thermal DM relic density;

$$\sigma(\psi p \to \psi p) \sim 2 \times 10^{-4} \text{ pb} \text{ and } \Omega h^2 \sim 0.1, \tag{3.4}$$

which would explain the DAMA signals without conflicting other null experiments, and also satisfy the measured DM mass density simultaneously. We also note that the lifetime of the singlet-like Higgs h_2 is much shorter than one second. Thus it decays well before the start of the Big Bang Nucleosynthesis, making no cosmological problem.

Now we scan our model parameters in a certain region, which provides a low singlet-like Higgs mass ($1\,\text{GeV} < m_{h_2} < 10\,\text{GeV}$), $m_{h_1} \sim 120\,\text{GeV}$ and small scalar mixing angle ($|\theta| < 0.02$) within a low DM mass range ($1\,\text{GeV} < m_\psi < 10\,\text{GeV}$). Figure 3 is the result of the parameter scan, showing the spin-independent cross section for DM-nucleon scattering as a function of the singlet fermionic DM mass m_ψ. In the figure, the red points are the predictions for the scattering cross section of singlet fermionic DM and they are required to satisfy the measured DM mass density (1.1). The cyan regions are consistent with the DAMA signals. Also denoted are the upper limits from various other null experiments. We clearly see that the singlet fermionic DM can explain the DAMA signals without conflicting with other null experiments and simultaneously satisfy the DM mass density which is consistent with the WMAP data.

4 Conclusion

We have shown that a simple model of light singlet fermionic dark matter can reconcile the DAMA signal with other null experiments, while providing a right amount of DM mass density which is consistent with the WMAP observation. The t-channel pair annihilation of the light dark matters to the pair of light singlet Higgs particles, with subsequent Higgs
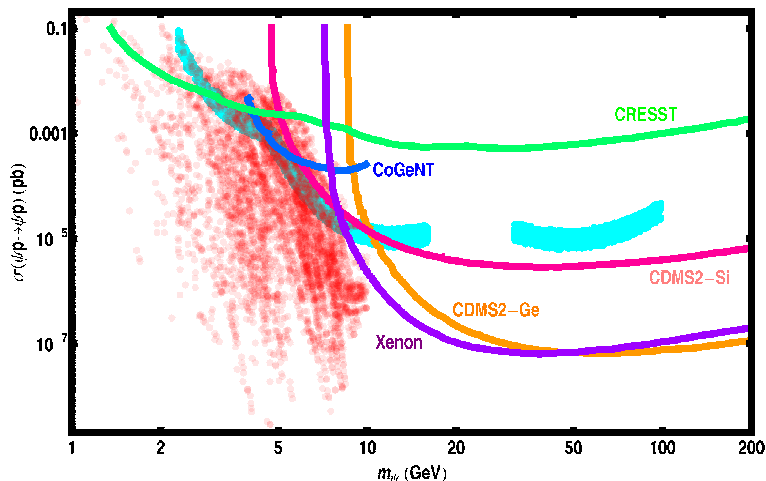
Figure 3. Spin-independent cross section for DM-nucleon scattering as a function of DM mass m_ψ. The red points are the predictions for the light singlet fermionic dark matter and the cyan regions are DAMA signal regions. Also denoted are the upper limits from various DM search experiments.

decays to the SM particles, would provide a large enough annihilation cross section to have a right amount of DM relic density. The light singlet fermionic DM, with the light singlet-like Higgs, can provide the spin-independent DM-nucleon scattering cross section which is compatible with the DAMA signal region and other null experiments, simultaneously.

Acknowledgments

References

[1] WMAP collaboration, J. Dunkley et al., *Five-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: likelihoods and parameters from the WMAP data*, *Astrophys. J. Suppl.* **180** (2009) 306 [arXiv:0803.0586] [SPIRES].

[2] A.K. Drukier, K. Freese and D.N. Spergel, *Detecting cold dark matter candidates*, *Phys. Rev.* **D 33** (1986) 3495 [SPIRES];
K. Freese, J.A. Frieman and A. Gould, *Signal modulation in cold dark matter detection*, *Phys. Rev.* **D 37** (1988) 3388 [SPIRES].

[3] DAMA collaboration, R. Bernabei et al., *First results from DAMA/LIBRA and the combined results with DAMA/NaI*, *Eur. Phys. J.* **C 56** (2008) 333 [arXiv:0804.2741] [SPIRES].

[4] XENON collaboration, J. Angle et al., *First results from the XENON10 dark matter experiment at the Gran Sasso national laboratory*, *Phys. Rev. Lett.* **100** (2008) 021303 [arXiv:0706.0039] [SPIRES].

[5] CDMS collaboration, Z. Ahmed et al., *Search for weakly interacting massive particles with the first five-tower data from the cryogenic dark matter search at the Soudan underground laboratory*, *Phys. Rev. Lett.* **102** (2009) 011301 [arXiv:0802.3530] [SPIRES].

[6] R. Bernabei et al., *Possible implications of the channeling effect in NaI(Tl) crystals*, *Eur. Phys. J.* **C 53** (2008) 205 [arXiv:0710.0288] [SPIRES];
E.M. Drobyshevski, *Channeling effect and improvement of the efficiency of charged particle registration with crystal scintillators*, *Mod. Phys. Lett.* **A 23** (2008) 3077 [arXiv:0706.3095] [SPIRES]; *DAMA/LIBRA findings urge replacement of the WIMP hypotheses by the daemon paradigm as a basis for experimental studies of DM objects*, *Mod. Phys. Lett.* **A 24** (2009) 177 [arXiv:0811.0151] [SPIRES].

[7] F. Petriello and K.M. Zurek, *DAMA and WIMP dark matter*, *JHEP* **09** (2008) 047 [arXiv:0806.3989] [SPIRES].

[8] P. Gondolo and G. Gelmini, *Compatibility of DAMA dark matter detection with other searches*, *Phys. Rev.* **D 71** (2005) 123520 [hep-ph/0504010] [SPIRES];
C. Savage, G. Gelmini, P. Gondolo and K. Freese, *Compatibility of DAMA/LIBRA dark matter detection with other searches*, *JCAP* **04** (2009) 010 [arXiv:0808.3607] [SPIRES].

[9] R. Foot, *Mirror dark matter and the new DAMA/LIBRA results: a simple explanation for a beautiful experiment*, *Phys. Rev.* **D 78** (2008) 043529 [arXiv:0804.4518] [SPIRES].

[10] J.L. Feng and J. Kumar, *The WIMPless miracle: dark-matter particles without weak-scale masses or weak interactions*, *Phys. Rev. Lett.* **101** (2008) 231301 [arXiv:0803.4196] [SPIRES];
J.L. Feng, J. Kumar and L.E. Strigari, *Explaining the DAMA signal with WIMPless dark matter*, *Phys. Lett.* **B 670** (2008) 37 [arXiv:0806.3746] [SPIRES].

[11] A. Bottino, F. Donato, N. Fornengo and S. Scopel, *Interpreting the recent results on direct search for dark matter particles in terms of relic neutralino*, *Phys. Rev.* **D 78** (2008) 083520 [arXiv:0806.4099] [SPIRES].

[12] D.G. Cerdeno, C. Munoz and O. Seto, *Right-handed sneutrino as thermal dark matter*, *Phys. Rev.* **D 79** (2009) 023510 [arXiv:0807.3029] [SPIRES].

[13] S. Chang, G.D. Kribs, D. Tucker-Smith and N. Weiner, *Inelastic dark matter in light of DAMA/LIBRA*, arXiv:0807.2250 [SPIRES];
J. March-Russell, C. McCabe and M. McCullough, *Inelastic dark matter, non-standard halos and the DAMA/LIBRA results*, arXiv:0812.1931 [SPIRES];
Y. Cui, D.E. Morrissey, D. Poland and L. Randall, *Candidates for inelastic dark matter*, arXiv:0901.0557 [SPIRES].

[14] Y.G. Kim, K.Y. Lee and S. Shin, *Singlet fermionic dark matter*, *JHEP* **05** (2008) 100 [arXiv:0803.2932] [SPIRES].

[15] Y.G. Kim and K.Y. Lee, *The minimal model of fermionic dark matter*, *Phys. Rev.* **D 75** (2007) 115012 [hep-ph/0611069] [SPIRES].

[16] M. Pospelov, A. Ritz and M.B. Voloshin, *Secluded WIMP dark matter*, *Phys. Lett.* **B 662** (2008) 53 [arXiv:0711.4866] [SPIRES];
W. Krolikowski, *Again on hidden sector of the universe, accessible through photonic portal*, *Acta Phys. Polon.* **B 40** (2009) 111 [arXiv:0809.1931] [SPIRES];

S. Andreas, T. Hambye and M.H.G. Tytgat, *WIMP dark matter, Higgs exchange and DAMA*, *JCAP* **10** (2008) 034 [`arXiv:0808.0255`] [SPIRES];
J.L. Feng, H. Tu and H.-B. Yu, *Thermal relics in hidden sectors*, *JCAP* **10** (2008) 043 [`arXiv:0808.2318`] [SPIRES];
P.-H. Gu, M. Hirsch, U. Sarkar and J.W.F. Valle, *Neutrino masses, leptogenesis and dark matter in hybrid seesaw*, `arXiv:0811.0953` [SPIRES];
J. McDonald and N. Sahu, Z_2-*singlino dark matter in a portal-like extension of the minimal supersymmetric standard model*, *JCAP* **06** (2008) 026 [`arXiv:0802.3847`] [SPIRES].

[17] S. Profumo, M.J. Ramsey-Musolf and G. Shaughnessy, *Singlet Higgs phenomenology and the electroweak phase transition*, *JHEP* **08** (2007) 010 [`arXiv:0705.2425`] [SPIRES].

[18] ALEPH, DELPHI, L3, OPAL, LEP working group for Higgs boson searches collaborations, R. Barate et al., *Search for the standard model Higgs boson at LEP*, *Phys. Lett.* **B 565** (2003) 61 [`hep-ex/0306033`] [SPIRES].

[19] S. Andreas, T. Hambye and M.H.G. Tytgat in ref. [16].

[20] M. Pospelov, A. Ritz and M. Voloshin in ref. [16].