Physics Letters B 750 (2015) 147–153

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Electroweak interacting dark matter with a singlet scalar portal

Cheng-Wei Chiang [a,b,c,d], Eibun Senaha [a,*]

[a] Center for Mathematics and Theoretical Physics and Department of Physics, National Central University, Taoyuan, 32001, Taiwan, ROC
[b] Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan, ROC
[c] Physics Division, National Center for Theoretical Sciences, Hsinchu, 30013, Taiwan, ROC
[d] Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan

ARTICLE INFO

Article history:
Received 20 August 2015
Received in revised form 29 August 2015
Accepted 4 September 2015
Available online 8 September 2015
Editor: J. Hisano

ABSTRACT

We investigate an electroweak interacting dark matter (DM) model in which the DM is the neutral component of the $\mathrm{SU}(2)_L$ triplet fermion that couples to the standard model (SM) Higgs sector via an SM singlet Higgs boson. In this setup, the DM can have a CP-violating coupling to the singlet Higgs boson at the renormalizable level. As long as the nonzero Higgs portal coupling (singlet-doublet Higgs boson mixing) exists, we can probe CP violation of the DM via the electric dipole moment of the electron. Assuming the $\mathcal{O}(1)$ CP-violating phase in magnitude, we investigate the relationship between the electron EDM and the singlet-like Higgs boson mass and coupling. It is found that for moderate values of the Higgs portal couplings, current experimental EDM bound is not able to exclude the wide parameter space due to a cancellation mechanism at work. We also study the spin-independent cross section of the DM in this model. It is found that although a similar cancellation mechanism may diminish the leading-order correction, as often occurs in the ordinary Higgs portal DM scenarios, the residual higher-order effects leave an $\mathcal{O}(10^{-47})$ cm^2 correction in the cancellation region. It is shown that our benchmark scenarios would be fully tested by combining all future experiments of the electron EDM, DM direct detection and Higgs physics.

1. Introduction

The existence of dark matter (DM) in the Universe is firmly established by cosmological and astronomical observations, with its relic abundance measured by the comic microwave background being [1]

$$\Omega_{\mathrm{CDM}}h^2 = 0.1198 \pm 0.0026\,, \tag{1}$$

where h is the reduced Hubble constant. In spite of the undoubted existence, we still do not know where to put the DM in the particle spectrum due to the lack of solid evidence from direct searches and identification of its quantum numbers.

Although the standard model (SM) is very successful in explaining most empirical observations in particle physics, one of its shortcomings is the absence of a DM candidate. To amend this, there have been many proposals to extend the SM with a dark sector, in which the lightest member, serving as a DM, cannot decay into SM particles due to some dark charge.

Weak-interacting massive particles (WIMPs) have attracted much attention as candidates for the DM because it is naturally accommodated in the TeV-scale physics. For example, non-singlet DMs under the $SU(2)_L \times U(1)_Y$ emerge in supersymmetric (SUSY) models such as the minimal supersymmetric SM (MSSM) (see, *e.g.*, Ref. [2] for a review). On the other hand, isospin singlet DMs commonly appear in the context of the Higgs portal scenarios in which the DMs can communicate with the SM particles only via the Higgs sector [3–10]. A lot of work has been done based on effective field theories or on specific renormalizable models, with both approaches complementary to each other. The former has a strong power in probing the dark sector in a model-independent way. However, some phenomena such as accidental cancellations due to light particles are often improperly described within this framework, and the latter is more appropriate to address such issues.

One of the unknown properties of the DM is its CP nature. In renormalizable fermionic DM Higgs portal scenarios, it is possible for the DM to have both scalar and pseudoscalar couplings (denoted by g^S and g^P, respectively). Explicitly, one may have

* Corresponding author.
E-mail addresses: chengwei@ncu.edu.tw (C.-W. Chiang), senaha@ncu.edu.tw (E. Senaha).

http://dx.doi.org/10.1016/j.physletb.2015.09.011
0370-2693/

$$S\overline{\chi^c}\Big(g^S + i\gamma_5 g^P\Big)\chi + \text{h.c.}\,, \tag{2}$$

where S is an isospin singlet scalar playing the role of messenger between the dark sector and Higgs sector, and the phase of fermionic DM field χ is already rotated so that its mass is real. If χ is a singlet under the SM gauge symmetry, it will be hard to probe CP violation in the dark sector as its effect appears only at loop levels in the Higgs sector. If χ participates in the electroweak interactions, on the other hand, we may detect the existence of such CP violation in electric dipole moment (EDM) experiments.

In EW-interacting DM (EWIMP) scenarios [11,12], the interactions between the DM and the gauge bosons are fixed by the ordinary gauge couplings, leaving the DM mass the only unknown parameter. However, the DM mass is also completely determined once the thermal relic scenario is assumed. For example, the DM mass should be around 3 TeV in the Wino case [11,12]. In the nonthermal relic scenario, on the other hand, the relic density could be explained by nonthermal production of the DM from heavier particles. In this case, it is conceivable that the DM mass can be as light as $\mathcal{O}(100)$ GeV.

In this Letter, we consider a model in which the DM resides in an $SU(2)_L$ triplet fermion with hypercharge $Y = 0$ (Wino-like DM)[1] and the interaction given in Eq. (2). Here we do not confine ourselves to the thermal relic scenario and, therefore, the DM mass is taken as a free parameter. In this framework, we study the CP-violating effects coming from the dark sector on the electron EDM in connection with Higgs physics. Throughout the analysis, the singlet scalar S is assumed to be lighter than 1 TeV. For the heavy S case, the interaction between χ and Higgs doublet (H) would be described by the dimension-5 operator $H^\dagger H\bar{\chi}^c(g'^S + i\gamma_5 g'^P)\chi/\Lambda$ after integrating out the S field. Recent studies on the connections between CP violation and the EWIMP using the effective Lagrangian can be found in Refs. [14,15].

The structure of this paper is as follows. In Section 2, we describe the DM model, with particular emphasis on the Higgs and dark sectors. Stability and global minimum conditions for the Higgs potential are discussed. We also provide the Higgs couplings with the SM particles and the triplet fermions. Section 3 discusses observables that can be used to constrain or test the model. Numerical results of these observables are presented in Section 4. Our findings are summarized in Section 5.

2. The model

We consider a model in which the DM candidate arises from an $SU(2)_L$ triplet (Wino-like) fermion field χ and couples to the SM Higgs sector via an $SU(2)_L$ singlet scalar field S. Both χ and S are assumed to carry no hypercharge. The relevant interactions are described by the Lagrangian

$$\begin{aligned}\mathcal{L} \supset &\left(D_\mu H^\dagger\right)\left(D^\mu H\right) + \mu_H^2 H^\dagger H - \lambda_H |H^\dagger H|^2 \\ &+ \frac{1}{2}\partial_\mu S\partial^\mu S + i\bar{\chi}^a\bar{\sigma}^\mu D_\mu \chi^a \\ &- \frac{1}{2}\Big[M\chi^a\chi^a + \lambda S\chi^a\chi^a + \kappa\tilde{H}^\dagger\frac{\tau^a}{2}\ell_L\chi^a + \text{h.c.}\Big] \\ &- \mu_S^3 S - \frac{m_S^2}{2}S^2 - \frac{\mu_S'}{3}S^3 - \frac{\lambda_S}{4}S^4 - \mu_{HS}H^\dagger HS \\ &- \frac{\lambda_{HS}}{2}H^\dagger HS^2\,,\end{aligned} \tag{3}$$

where χ^a denote 2-component spinors, $\tilde{H} = i\sigma^2 H^*$ and $\bar{\sigma}^\mu = (1, -\sigma^i)$ with σ^i being the Pauli matrices, and the covariant derivative acting on the field χ^a is

$$D_\mu\chi^a = \partial_\mu\chi^a - g_2\epsilon^{abc}A_\mu^b\chi^c\,, \tag{4}$$

with g_2 being the $SU(2)_L$ gauge coupling. We impose the Z_2 symmetry, $\chi \to -\chi$, so that the third term involving the lepton doublet ℓ_L in the square bracket of Eq. (3) drops out, and the neutral component of χ becomes a DM candidate. Phenomenology of DM without the singlet Higgs boson is well studied (see, for example, Refs. [11,12]).

We parameterize the Higgs fields as follows:

$$H(x) = \begin{pmatrix} G^+(x) \\ \frac{1}{\sqrt{2}}\big(v + h(x) + iG^0(x)\big)\end{pmatrix}, \quad S(x) = v_S + h_S(x)\,, \tag{5}$$

where $v = 246$ GeV, and G^+ and G^0 are the Nambu–Goldstone bosons. The Higgs sector of this model is the same as the real singlet-extended SM (rSM). Here we give a quick review of rSM to make the paper self-contained. The tadpole conditions are

$$\left\langle\frac{\partial V}{\partial h}\right\rangle = v\left[-\mu_H^2 + \lambda_H v^2 + \mu_{HS}v_S + \frac{\lambda_{HS}}{2}v_S^2\right] = 0\,, \tag{6}$$

$$\begin{aligned}\left\langle\frac{\partial V}{\partial h_S}\right\rangle &= v_S\left[\frac{\mu_S^3}{v_S} + m_S^2 + \mu_S' v_S + \lambda_S v_S^2 + \frac{\mu_{HS}}{2}\frac{v^2}{v_S} + \frac{\lambda_{HS}}{2}v^2\right] \\ &= 0\,,\end{aligned} \tag{7}$$

where $\langle\cdots\rangle$ means that the quantity in the bracket is evaluated in the vacuum. These two tadpole conditions can be used to solve for μ_H^2 and m_S^2 in terms of the other parameters. Assuming $v, v_S \neq 0$, the squared-mass matrix of the Higgs bosons in the vacuum is cast into the form

$$\mathcal{M}_H^2 = \begin{pmatrix} 2\lambda_H v^2 & \mu_{HS}v + \lambda_{HS}vv_S \\ \mu_{HS}v + \lambda_{HS}vv_S & -\frac{\mu_S^3}{v_S} + \mu_S' v_S + 2\lambda_S v_S^2 - \frac{\mu_{HS}}{2}\frac{v^2}{v_S}\end{pmatrix}, \tag{8}$$

which can be diagonalized by an orthogonal matrix as

$$O(\alpha)^T\mathcal{M}_H^2 O(\alpha) = \begin{pmatrix} m_{H_1}^2 & 0 \\ 0 & m_{H_2}^2\end{pmatrix},$$

$$O(\alpha) = \begin{pmatrix}\cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha\end{pmatrix}, \tag{9}$$

where $-\pi/4 \le \alpha \le \pi/4$. Here we assume that the mass eigenvalues satisfy $m_{H_1} < m_{H_2}$, and $m_{H_1} = 125$ GeV. The scenario of no mixing between the H and S fields ($\alpha \to 0$) occurs in both the alignment limit $\mu_{HS} = -\lambda_{HS}v_S$ and the decoupling limit $-\frac{\mu_S^3}{v_S} + \mu_S' v_S + 2\lambda_S v_S^2 - \frac{\mu_{HS}}{2}\frac{v^2}{v_S} \gg 2\lambda_H v^2$.

The tree-level effective potential is given by

$$\begin{aligned}V_0(\varphi, \varphi_S) = &-\frac{\mu_H^2}{2}\varphi^2 + \frac{\lambda_H}{4}\varphi^4 + \frac{\mu_{HS}}{2}\varphi^2\varphi_S + \frac{\lambda_{HS}}{4}\varphi^2\varphi_S^2 \\ &+ \mu_S^3\varphi_S + \frac{m_S^2}{2}\varphi_S^2 + \frac{\mu_S'}{3}\varphi_S^3 + \frac{\lambda_S}{4}\varphi_S^4\,,\end{aligned} \tag{10}$$

where φ and φ_S are respectively the classical background fields of h and h_S, and μ_H^2 and m_S^2 are given by Eqs. (6) and (7). In order for the potential to be bounded from below, we impose the following conditions on the quartic couplings:

$$\lambda_H > 0\,, \quad \lambda_S > 0\,, \quad -2\sqrt{\lambda_H\lambda_S} < \lambda_{HS}\,, \tag{11}$$

where the last condition is needed in particular when λ_{HS} takes negative values. Since $V_0(\varphi, \varphi_S)$ is not symmetric under the transformation $\varphi_S \to -\varphi_S$, it is possible for $V_0(\varphi, \varphi_S)$ to have another

[1] Other than SUSY and inspired models, the $SU(2)_L$ triplet fermions also emerge in a specific DM model that achieves gauge coupling unification [13].