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Future detectability of a pseudoscalar mediator dark matter model

T Abe[1,2], M Fujiwara[3], J Hisano[2,3,4], Y Shoji[2]

[1]Institute for Advanced Research, Nagoya University, Furo-cho Chikusa-ku, Nagoya, 464-8602 Japan
[2]Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Furo-cho Chikusa-ku, Nagoya, 464-8602 Japan
[3]Department of Physics, Nagoya University, Furo-cho Chikusa-ku, Nagoya, 464-8602 Japan
[4]Kavli IPMU (WPI), UTIAS, University of Tokyo, Kashiwa, 277-8584, Japan

E-mail: `motoko@eken.phys.nagoya-u.ac.jp`

Abstract. We investigate the maximum value of the spin-independent cross section in a dark matter (DM) model called the two-Higgs doublet model + a (THDM+a). This model can explain the observed DM energy density while evading the current strict bound from the DM direct detection experiment because the predicted cross section at the tree-level is highly suppressed by the momentum transfer. On the other hand, the loop induced scattering effects are predicted without momentum suppression and might be detectable in the future DM direct detection experiments. The predicted cross section strongly depends on the scalar quartic couplings. We derive the theoretical constraints on these parameters by studying the stability of the electroweak vacuum, and the condition for the potential bounded from below. Considering these constraints, we find that the maximum value of the predicted cross section is larger than the prospects of the LZ and XENONnT experiments and this model has the potential to explain the DM direct detection signal which might be obtained near future.

1. Introduction

There is overwhelming evidence that the dark matter (DM) exists in our universe. The energy density of DM is precisely determined by the observation of the Planck collaboration, $\Omega h^2 = 0.120 \pm 0.001$ [1]. The measured value is explained successfully by DM models that use the freeze-out mechanism [2]. Those models generally predict non-zero DM-nucleon scattering cross section and have been searched by the DM direct detection experiments, such as the XENON1T experiment [3]. However, no significant signals have been observed until now, and the null results set upper bound on the DM-nucleon scattering cross section. The latest result by the XENON1T experiment gives a severe constraint on DM models.

If a DM particle is a gauge singlet fermion, χ, and couples to a scalar mediator, a_0, with pseudoscalar type interaction, $\bar{\chi} i \gamma_5 \chi a_0$, then it is possible to avoid this strong constraint from the XENON1T experiment while keeping the success of the freeze-out mechanism [4, 5]. The two-Higgs doublet model + a (THDM+a) [6] is one of the models that realize this idea. In addition to the introduction of the DM and the mediator, the Higgs sector is extended into the two-Higgs doublet model. The CP invariance is assumed in the dark sector and the scalar sector. Then, the dark sector and the visible sector can interact through the mixing between

a_0 and the CP-odd scalar (A_0) in the two-Higgs doublet sector. The model predicts rich phenomenology [7, 8, 9, 10, 11, 12, 13, 14], and it is summarized in Ref. [15].

The THDM+a predicts non-zero spin-independent DM-nucleon scattering cross section ($\sigma_{\rm SI}$) at the loop level [6, 11, 13, 14, 16]. In particular, it was shown that if the scalar quartic couplings between a_0 and Higgs doublet fields (H_1 and H_2), $a_0^2 H_1^\dagger H_1$ and $a_0^2 H_2^\dagger H_2$, are large enough, the model can be tested at the forthcoming DM direct detection experiments [16]. However, these quartic couplings are directly related to the vacuum structure of the scalar potential, and we cannot take arbitrarily large values of them.

We study the constraints on the scalar potential from the stability of the electroweak vacuum, and the boundedness of the potential. Using these constraints, we investigate the upper and the lower bounds on the scalar quartic couplings, and discuss the detectability of this model in the future DM direct detection experiments, such as the LZ experiment [17] and the XENONnT experiment [18].

2. Model

The model contains a gauge singlet Majorana fermion χ as a DM candidate, with its mass m_χ, and a CP-odd gauge singlet scalar a_0 as a mediator. The standard model (SM) Higgs sector is extended into the two-Higgs doublet model. We assume CP invariance both in the dark sector and in the scalar sector. This assumption guarantees that the Yukawa interaction between χ and a_0 is always pseudoscalar interaction. The scalar potential is as follows.

$$\begin{aligned} V =& m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - m_3^2 \left(H_1^\dagger H_2 + (h.c.) \right) \\ &+ \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ &+ \frac{1}{2}\lambda_5 \left((H_1^\dagger H_2)^2 + (h.c.) \right) \\ &+ \frac{1}{2} m_{a_0}^2 a_0^2 + \frac{\lambda_a}{4} a_0^4 + \kappa \left(i a_0 H_1^\dagger H_2 + (h.c.) \right) + c_1 a_0^2 H_1^\dagger H_1 + c_2 a_0^2 H_2^\dagger H_2. \end{aligned} \tag{1}$$

Since we assume the CP invariant scalar potential, all the coupling constants in the potential are real. In this paper, we assume that the thermal relic abundance of χ explains the measured value of the DM energy density [1], and g_χ is fixed to realize it for a given parameter set by the freeze-out mechanism.

We impose the condition that the potential has the electroweak vacuum,

$$\langle a_0 \rangle = 0, \ \langle H_1 \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v \cos\beta \end{pmatrix}, \ \langle H_2 \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v \sin\beta \end{pmatrix}, \tag{2}$$

where $v \sim 246$ GeV. It is also important that a_0 does not develop a vacuum expectation value. Otherwise, the scalar-type Yukawa interaction is induced in the dark sector due to the scalar and pseudoscalar mixing, and the model is strongly constrained from the DM direct detection experiments.

After the electroweak symmetry breaking, there are six physical scalars: two CP-even scalars (h and H), two CP-odd scalars (a and A), and a pair of charged scalars ($H^\pm$). The physical masses for h, H, a, A, and $H^\pm$ are denoted to m_h, m_H, m_a, m_A, and $m_{H^\pm}$, respectively. The two CP-odd scalars are mixtures of the CP-odd neutral components in H_1 and H_2 and also a_0. Its mixing angle is denoted by θ. These pseudoscalars mediate the interaction between χ and SM particles. In the following, we take the so-called alignment limit, in which the model predicts the same hWW and the hZZ couplings as in the SM. We also take $m_H = m_A = m_{H^\pm} (\ \equiv m_{H,H^\pm,A})$ to satisfy the constraints from the electroweak precision measurement. The more details about the treatment of the parameters are given by Ref. [19].

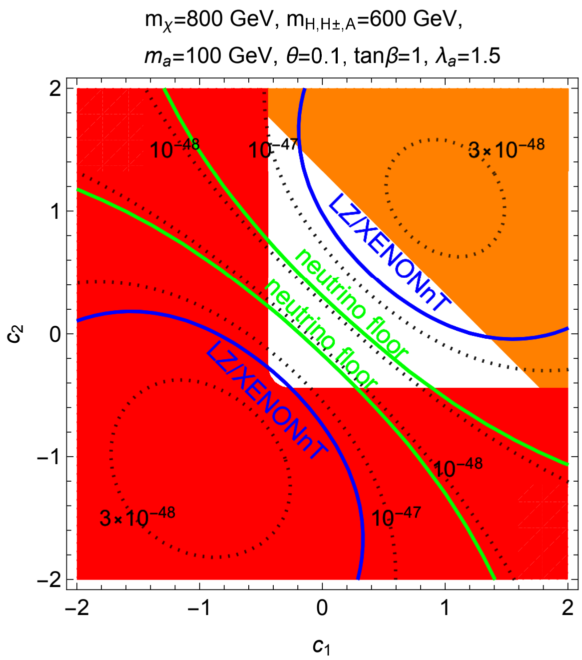

Figure 1. The contours of $\sigma_{\rm SI}$ [cm^2] for $m_\chi = 800$ GeV. The blue solid lines show the LZ and XENONnT prospects [17, 18], We take $m_{H,H^\pm,A} = 600$ GeV, $m_a = 100$ GeV, $\theta = 0.1$, $\tan\beta = 1$, and $\lambda_a = 1.5$. The region between two green lines is below the neutrino floor [20]. The global minimum does not break the electroweak symmetry in the orange shaded region. In the red shaded region, the scalar potential is unbounded from below.

3. Theoretical constraints on the scalar potential

We study the theoretical constraints on the scalar potential. First, we consider the stability of the electroweak vacuum. We have numerically performed the global minimum search in the parameter space and obtain the upper bound on c_1 and c_2. If we take large positive values of c_1 and c_2, the following configuration realizes the global minimum instead of the electroweak vacuum configuration.

$$\langle H_1 \rangle = \langle H_2 \rangle = 0, \quad \langle a_0 \rangle \neq 0. \tag{3}$$

Second, we consider the bounded from below conditions of the potential. The potential should be positive for the region where the field values are extremely large. From this requirement, the constraints for the scalar quartic couplings are obtained. The explicit formulas of these conditions are given in Ref. [19]. In particular, negatively large values of c_1 and c_2 are severely constrained.

4. Result

Figure 1 shows the contours of $\sigma_{\rm SI}$ for $m_\chi = 800$ GeV with the conditions discussed in Sec. 3. The other parameters except λ_a are the same as one used in Fig. 8 in Ref. [16], namely $m_{H,H^\pm,A} = 600$ GeV, $m_a = 100$ GeV, $\tan\beta = 1$, $\theta = 0.1$, and $\lambda_a = 1.5$. It is clearly shown that $\sigma_{\rm SI}$ is larger in the larger $|c_i|$ $(i = 1, 2)$ region as discussed in Ref. [16]. It is also shown that there is an upper bound on $\sigma_{\rm SI}$ from the condition discussed in Sec. 3. Large positive values of c_i predict that the electroweak vacuum is not the global minimum. This is because such large positive values of c_i make $m_{a_0}^2$ negatively large, and thus the configuration shown in Eq. (3) realizes the global minimum of the potential instead of the electroweak vacuum. Large negative values of c_i make the potential unbounded from below. These theoretical constraints on the scalar potential give the upper and lower bounds on c_i. Consequently, $\sigma_{\rm SI}$ cannot be arbitrary large. Nevertheless, we still find that the maximum value of $\sigma_{\rm SI}$ is above the prospect lines of the LZ and XENONnT experiments [17, 18].

5. Conclusions

We have studied the theoretical constraints for the scalar potential of the THDM+a and discussed the detectability of this model in the future DM direct detection experiments, such as the LZ and XENONnT experiments. We have considered the stability of the electroweak vacuum, and the conditions for the potential to be bounded from below. As shown in Fig. 1, large values of $|c_1|$ and $|c_2|$ make $\sigma_{\rm SI}$ larger. However, the condition for the stability of the electroweak vacuum gives upper bounds on c_1 and c_2, and the potential boundedness condition gives lower bounds on them. As a result, the maximum value of $\sigma_{\rm SI}$ exists for a given parameter set. We also found that the maximum value is larger than the prospects of the LZ and XENONnT experiments. Therefore, if these experiments observe the DM signal in the future, then this model has the potential to explain the signal.

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