Scalar Dark Matter Candidates in Two Inert Higgs Doublet Model

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Abstract: We study a two scalar inert doublet model (IDMS$_3$) which is stabilized by a $S_3$ symmetry. We consider two scenarios: i) two of the scalars in each charged sector are mass degenerated due to a residual $Z_2$ symmetry, ii) there is no mass degeneracy because of the introduction of soft terms that break the $Z_2$ symmetry. We show that both scenarios provide good dark matter candidates for some range of parameters.

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1 Introduction

The existence of dark matter (DM) has been well established since the early astronomical [1] and cosmological observations [2–5]. For more recent data see [6]. It accounts for approximately 23% of the composition of the universe. Moreover, these observational evidence justify the experimental searches trying to find events that can be interpreted as direct manifestations of DM. Some of them are astronomical observations [7–11], and others like DAMA [12], CoGeNT [13], CDMS [14], XENON [15, 16], and LUX [17] are experiments trying to measure the recoil energy of nuclei if it scatters with the DM.

Models which contain DM candidates have to explain among other aspects, the DM density, which is
\[ \Omega h^2 = \rho h^2 / \rho_c = 0.1196 \pm 0.0031 \]
where, \( h \) is the scale factor for Hubble expansion [18], \( \rho_c = 3H_0^2 / (8\pi G) \) is the critical density of the Universe, and \( H_0 \) is the current value of the Hubble constant [6].

Much effort has been employed in order to discover or interpreted DM signals. It is possible that it consists of one or more elementary particles which interact very weakly with ordinary matter. One of the most common scenarios are supersymmetric models [19]. In fact, in this kind of models the lightest supersymmetric particle (neutralino) is prevented by the \( R \) parity to interact with the known particles. The neutralino is an example of cold dark matter (CDM), i.e. a kind of DM which is not relativistic at the time of freeze out. Of course, there are other possibilities, for instance, Kaluza-Klein states in models with universal [20, 21] or warped [22] extra dimensions, stable states in little Higgs theories [23] and a number of models with extra heavy neutrinos. Some other alternative scenarios for DM consider self-interacting DM [25] and warm DM [24]. Other ambitious scenarios consider asymmetric dark matter models. They have their motivation based on the similarity of mass densities of the DM (\( \rho_{DM} \)) and that of the visible matter (\( \rho_B \)) observed
\[ \rho_{DM} / \rho_B \approx 5 \]
and try to explain this rate. Consequently, most of these models are based on the hypothesis that the present abundance of DM and visible matter have the same origin [26, 27].

An additional and interesting scenario which contains DM candidates is the inert doublet model (IDM) [28–32]. It is a minimal extension of the SM which contains a second Higgs doublet
(H_2) with no direct couplings to quarks and leptons. The first time that the phenomenology of an inert doublet was considered was in the context of neutrino physics [33] and also in the context of the problem of naturalness [34]. In all cases, the inert doublet was possible due to a Z_2 symmetry under which H_2 → -H_2 and all the other fields are even. In particular, this discrete symmetry forbids interactions like (H_1^†H_2)(H_2^†H_2), being H_1 the SM Higgs doublet.

In this work, we study the three Higgs doublet model with a S_3 symmetry, proposed in [35], in which, besides the standard model-like doublet there are two additional inert doublets, here denoted H_2 and H_3. It is this S_3 symmetry and an appropriate vacuum alignment that allows us to obtain a model with two inerts doublets. Besides, we already know from IDM models that this new particles have a rich phenomenology, especially as a good dark matter candidate. Here we will show that the same can happens in a model with two inert doublets. We will analyze two scenarios for this model, one in which the extra scalars are mass degenerated and the other in which soft terms, breaking a residual Z_2 symmetry, are added, resulting in non degenerated masses for this extra scalars.

The paper is organized as follows. In Sec. 2 we briefly present the model. In Sec. 3 we briefly describe the theoretical framework for the calculations for DM abundance and in the Sec. 4 we show the parameter choices suitable for the dark matter candidate and the numerical results. Finally in the last section section, Sec. 5, we summarize our conclusions.

2 The Model

In the context of standard model (SM) the number of scalar doublets can be arbitrary. An interest case is that the number of these fields is the same as the number of the fermion families, i.e. just three. In this case, as we said before, the S_3 symmetry is, probably, the most interesting one because it is the minimal non-abelian discrete symmetry with one doublet and one singlet irreducible representations.

The model that we will consider here has the three Higgs doublets transforming as (2, +1) under SU(2)_L ⊗ U(1)_Y and under S_3 as:

\[ S = H_1 \sim 1, \]
\[ (D_1, D_2) = (H_2, H_3) \sim 2. \]  

(2.1)

This case was called Case B in Ref. [35] and we will be restricted to this case in the present paper. The necessary conditions under which the vacuum alignment v_1 = v_{SM}, v_{SM} is the SM VEV \sim 246 GeV and v_2 = v_3 = 0, allow a scalar potential bounded from below and a stable minimum as has been shown in Ref. [35]. With this vacuum alignment and, since the quarks and leptons are singlet of S_3, the two Higgs doublet D_1, D_2 do not couple to fermions and do not contribute to the spontaneous symmetry breakdown, i.e they are inerts. They couple only to the gauge bosons and this vacuum alignment also implies in a residual Z_2 symmetry in which the two inert doublets are
mass degenerate in each charged sector. In this case the mass spectra is

\[ m^2_{H_0^2} = m^2_{H_0^3} = \mu_d^2 + \frac{1}{2} \lambda' v_{SM}^2, \]

\[ m^2_{A_2} = m^2_{A_3} = \mu_d^2 + \frac{1}{2} \lambda'' v_{SM}^2, \]

\[ m^2_{h^1_2} = m^2_{h^1_3} = \frac{1}{4} (2\mu_d^2 + \lambda S v_{SM}^2), \]

(2.2)

where \( \mu_d^2 \) came from the term \( \mu_d^2 [D^\dagger D_1] \) in the scalar potential, with \( \lambda' = \lambda_5 + \lambda_6 + 2\lambda_7 \) and \( \lambda'' = \lambda_5 + \lambda_6 - 2\lambda_7 \), with \( \lambda_{5,6,7} \) are quartic coupling constants in the scalar potential. We call this Scenario 1.

If the residual \( Z_2 \) symmetry is softly broken by adding non-diagonal quadratic terms in the inert sector, the mass degeneracy is broken and the mass spectra becomes

\[ m^2_{H_0^2} = m^2_{H_0^3} - \nu^2, \quad m^2_{H_0^3} = m^2_{H_0^1} + \nu^2, \]

\[ m^2_{A_2} = m^2_{A_3} - \nu^2, \quad m^2_{A_3} = m^2_{A_1} + \nu^2, \]

\[ m^2_{h^1_2} = m^2_{h^1_3} - \nu^2, \quad m^2_{h^1_3} = m^2_{h^1_1} + \nu^2, \]

(2.3)

and we call this Scenario 2.

In the case of mass degenerate scalars, the lightest scalars can be DM candidates and we will choose the \( CP \) even ones. In the case of no mass degeneracy it is possible that the lightest one is the DM candidate. For the Scenario 1, our parameter choice enables us to establish the follow order for the mass of the scalars: \( m_{A_{2,3}} > m_{h^1_{2,3}} > m_{H^0_{2,3}} \). Since \( H^0_{2,3} \) are the lightest neutral scalars, their decays are kinematically forbidden. With the rearrangement of the parameters, instead of choosing \( H^0_{2,3} \), we could choose the \( CP \) odd scalars \( A_{2,3} \) as the DM candidates, if they were the lightest ones, and the same conclusions would remain valid for this scenario. In the Scenario 2, \( H^0_2 \) accounts for all the \( \Omega_{DM} h^2 \) contribution. In each scenario we choose two set of parameters as is shown in Table 1.

### 3 Dark Matter Abundance

Preliminary analysis showing that this model can accommodate dark matter candidates were done in Ref. [35]. Here, this will be confirmed by a more detailed analysis. In order to calculate the DM abundance we have used the MicrOMEGAs package to solve numerically the Boltzmann equation after implementing all the interactions of the model in the CalcHEP package [36].

Let us consider for instance, the model of inert doublets with non degenerated mass (Scenario 2). In this case, as we already said in Sec. 2, \( H^0_2 \) is our DM candidate. The evolution of the numerical density \( n \) of \( H^0_2 \), at the temperature \( T \) in the early Universe, is given by the Boltzmann equation, which is written in simplified form as follows [37]:

\[ \frac{dY}{dy} = - \sqrt{\frac{\pi g_* m_{H^0_2}}{45G y^2}} \langle \sigma_{\text{ann}} v \rangle (Y^2 - Y_{eq}^2), \]

(3.1)

here \( Y = n/s \), \( s \) is the entropy per unity of volume, \( Y_{eq} \) is the \( Y \) value in the thermal equilibrium, \( y = m_{H^0_2}/T \). The parameter \( G \) in Eq. (3.1) is the Newton gravitational constant, \( \sigma_{\text{ann}} \) is the cross
section for annihilation of the particle $H_2^0$ and $v$ is the relative velocity, and the symbol $\langle \rangle$ represents thermal average. Finally, $g_s$ is a parameter that measures the effective number of degrees of freedom at freeze-out, which is expressed as

$$
g_s = \sum_{i=\text{bosons}} g_i \left( \frac{T}{T} \right)^4 + \frac{7}{8} \sum_{i=\text{fermions}} g_i \left( \frac{T}{T} \right)^4,
$$

where the sums runs over only those species with mass $m_{H_2^0} \ll T$ [38]. The model studied here has, besides the SM particles, 8 extra scalars ($A^0_2, A^0_3, H_2^0, H_3^0, h^+_2, h^+_3$). So, considering, for instance $T \geq 300$ GeV we obtain $g_s \approx 114.75$.

To find $Y_0$, the present value of $Y$, Eq. (3.1) must be integrated between $y = 0$ and $y_0 = m_{H_2^0}/T_0$. Once this value is found, the contribution of $H_2^0$ to DM density is

$$
\Omega_{h_2} = \frac{m_{H_2^0}^2 s_0 Y_0}{\rho_c},
$$

The same calculations hold for the Scenario 1.

4 Results and Comments

The main numerical results for this model are presented in this section. We present in Table 1 the parameters choice for both scenarios. The interactions and Feynman rules can be found in Ref. [39]. For both scenarios (1 and 2), we have considered some set of parameters, so we call these scenarios respectively scenario 1a, 1b and scenario 2a, 2b and 2c.

For scenario 1a, the dominant annihilation channels are: 39% relative to $H_1^0 H_1^0 \rightarrow b\bar{b}$, 39% to $H_2^0 H_2^0 \rightarrow b\bar{b}$, 5% to $H_2^0 H_3^0 \rightarrow GG$, 5% to $H_3^0 H_3^0 \rightarrow GG$, 4% to $H_2^0 H_3^0 \rightarrow \tau^+ \tau^-$, 4% to $H_2^0 H_2^0 \rightarrow \tau^\pm \tau^\mp$, 2% to $H_3^0 H_3^0 \rightarrow c\bar{c}$ and 2% due to $H_2^0 H_2^0 \rightarrow c\bar{c}$. The contribution of the two candidates ($H_1^0, H_2^0$) to the Higgs invisible decay is 34.8%. The Higgs invisible decay depends strongly on the parameter $\lambda'$. In scenario 1, another choice of parameters which brings null contributions to this invisible decay is reached with the numbers presented in the scenario 1b. The dominant annihilation channels are in this case 50% relative to $H_1^0 H_1^0 \rightarrow W^+ W^-$ and 50% relative to $H_1^0 H_1^0 \rightarrow W^+ W^-$. Next we consider Scenario 2, in which $H_2^0$ is the only DM candidate. In Scenario 2a, the dominant annihilation channels are respectively 77% relative to $H_2^0 H_2^0 \rightarrow b\bar{b}$, 11% to $H_2^0 H_2^0 \rightarrow GG$, 8% to $H_2^0 H_2^0 \rightarrow \tau^+ \tau^-$ and 3% due to $H_2^0 H_2^0 \rightarrow c\bar{c}$. In this scenario, $H_2^0$ doesn’t contribute to the Higgs invisible decay.

For all the scenarios discussed above, the Cold DM-nucleons amplitudes are in agreement with CoGent, DAMA, LUX, XENON100. The Scenario 2b and 2c are in agreement with the predictions of XENON1T for $\sigma S$. In scenario 2b, the dominant annihilation channels are 78% relative to $H_2^0 H_2^0 \rightarrow b\bar{b}$, 10% relative to $H_2^0 H_2^0 \rightarrow GG$, 8% relative to $H_2^0 H_2^0 \rightarrow \tau^+ \tau^-$ and 3% relative to $H_2^0 H_2^0 \rightarrow c\bar{c}$. In scenario 2c, the dominant annihilation channel is 100% due to $H_2^0 H_2^0 \rightarrow W^+ W^-$. In this scenario, a negative $\lambda_5$ favors mainly the Higgs decay into two neutral gauge bosons [39]. Due to the smallness of $\lambda' = 0.001$, in scenario 2b the branching $h \rightarrow H_2^0 H_2^0$ is negligible ($\approx 5 \times 10^{-4}$), since this Higgs decay is very sensible to this parameter.

The Fig. 1 shows the data presented in Table1 compared to the experimental results for $\sigma S$ considered in the experiments CoGent, DAMA, LUX, XENON100 and XENON1T.
5 Conclusion

Here we have considered a two inert doublet model with an $S_3$ symmetry. The model has, besides the SM particles, eight scalars bosons which are inert, i.e. they do not contribute to the spontaneous electroweak symmetry breaking. They interact only with the gauge bosons through trilinear and quartic interactions, here only the latter one is important. In the case of degenerated masses (Scenario 1), two neutral scalars play the role of DM and in the case of non-degenerated masses (Scenario 2), one of the neutral scalars is the DM candidate. Besides these candidates, depending on the parameter choice, the model can also accommodate pseudoscalars DM candidates. It is well known that in the one inert doublet model there exist a set of allowed parameters in which we have a dark matter candidate, and, in particular, that there are three allowed regions of masses that are compatible with observed value of $\Omega_{DM}h^2$ and $R_{\gamma\gamma}$: i) $\lesssim 10$ GeV; ii) 40-150 GeV, and iii) $\gtrsim 500$ GeV [40]. Here we have proved that the IDMS$_3$ also has DM candidates at least in the second region, the analysis of the other regions will be considered elsewhere.

We have analyzed, as an illustration, some possible set of parameters in both scenarios for the scalars contributions to $\Omega_{DM}h^2$. We call them Scenario 1a, 1b, 2a, 2b and 2c. It can be seen from the Table and the figure that the spin-independent elastic cross section, $\sigma^{SI}$, is in good agreement with the results of experiments LUX and XENON100 for the mass range of DM considered here. We also have presented scenarios (2b and 2c) where the predictions of XENON1T, to be measured in the future, are matched. The cross section $\sigma^{SI}$, as can be seen from the Table1, are strongly dependent of the parameter $\lambda'$.

The contribution to the ratio $R_{\gamma\gamma}$ in the present model has interesting differences compared to one inert doublet and that will be shown elsewhere [39].

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|          | scenario 1a | scenario 1b | scenario 2a | scenario 2b | scenario 2c |
|----------|-------------|-------------|-------------|-------------|-------------|
| $m_{H_1^0}$ | 54.1        | 79.9        | 63.4        | 59.1        | 168         |
| $m_{H_1^0}$ | 54.1        | 79.9        | 86.59       | 83.47       | 178.04      |
| $m_{A_2^0}$ | 112.44      | 127.95      | 117.19      | 117.25      | 196.16      |
| $m_{A_1^0}$ | 112.44      | 127.95      | 131.19      | 131.24      | 204.83      |
| $m_{h_1^0}$ | 85.02       | 95.36       | 101.89      | 101.92      | 103.21      |
| $m_{h_3^0}$ | 85.02       | 95.36       | 101.89      | 101.92      | 103.21      |
| $\mu_d$   | 48.53       | 78.1        | 72          | 72.1        | 173         |
| $\nu$     | –           | –           | 41.7        | 41.7        | 41.7        |
| $\lambda'$| 0.019       | 0.009       | 0.019       | 0.001       | 0.001       |
| $\Omega$  | 0.11        | 0.11        | 0.108       | 0.11        | 0.11        |
| $\sigma v$| 0.0832      | 0.003       | 6.17        | 0.0013      | 0.74        |
| $\sigma_{SI}^{proton}$ | $7.33 \times 10^{-46}$ | $7.44 \times 10^{-47}$ | $5.31 \times 10^{-46}$ | $1.7 \times 10^{-48}$ | $2.019 \times 10^{-49}$ |
| $\sigma_{SI}^{neutron}$ | $8.38 \times 10^{-46}$ | $8.52 \times 10^{-47}$ | $6.08 \times 10^{-46}$ | $1.9 \times 10^{-48}$ | $2.32 \times 10^{-49}$ |

Table 1. Parameters choice for Scenario 1 and 2 with $m_h = 125$ GeV. The other masses units are in GeV, $\sigma v$ is in units of $10^{-26}$ cm$^2$/s and the units for $\sigma_{SI}$ are in cm$^2$. The parameters $\lambda'' = 0.34$ and $\lambda_5 = 0.4$ for scenarios 1a, 1b, 2a, 2b and $\lambda_5 = -0.4$ for scenario 2c.
Figure 1. Limits for $\sigma_{SI}$ according to the experiments CoGeNT, DAMA, XENON100, XENON1T and LUX.
The points $X_{1a}$, $X_{1b}$, $X_{2a}$, $X_{2b}$ and $X_{2c}$ are the ones refer to scenarios 1a, 1b, 2a, 2b and 2c given in Table 1.