Dark Matter candidate in Inert Doublet Model with additional local gauge symmetry $U(1)$

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Abstract. We consider the Inert Doublet Model (IDM) with an additional local gauge symmetry $U(1)$ and a complex singlet scalar to break the symmetry $U(1)$. The continuous symmetry $U(1)$ is introduced to control the CP-conserving interaction instead of some discrete symmetries as usually. We present the mass spectrum for neutral scalar and gauge bosons and the values of the charges under $U(1)$ for which the model could have a candidate to dark matter.

1. Introduction

The existence of Dark matter (DM) is now essentially established [1]. The most convincing evidence for DM came from the observation that luminous objects such as stars, gas clouds, globular clusters, or entire galaxies move faster than one would expect if they only felt the gravitational attraction of other visible objects [2, 3]. DM is estimated to constitute about 23% of the total matter in the universe. However, the origin of DM still remains a mystery.

The Standard Model (SM) of particle physics successfully explains experimental results observed in colliders, but none of the SM particles can be a good candidate for the dark matter. One of the main reasons is the lack of particles with scarce or null interactions with other SM particles. One of the first proposals for DM candidate within the content of SM particles...
were neutrinos but these have been discarded because they do not fit the description of hot DM. Therefore, it is necessary to look for new physics beyond the SM. In the literature there are various proposals as dark matter candidates, being a weakly interacting massive particle (WIMP) a promising candidate; in fact, the WIMP relic density is around the observed value (Planck Collaboration) \[4\]:

\[
\Omega h^2_{CDM} = 0.1199 \pm 0.0027.
\]

In the case of WIMPs as DM candidates in models beyond the standard model we comment some of them below. In supersymmetric models, one candidate is the lightest neutralino as a spin-1/2 WIMP dark matter \[5\]. Spin-1 WIMP dark matter has been studied in the context of models with extra dimensions \[6\]. Some extensions are focused to only include scalar fields in different representations under \(SU(2)_L\) \[7, 8, 9\]; if these scalars are stable, they can in principle account for a density of DM. These last proposals have been taken into account more seriously because current experimental constraints and possible future observations for scalar particles.

Several new physics scenarios with extended scalar fields and extra Higgs doublets have been considered to accommodate new particles as DM candidates. For example, the Inert Two Higgs Doublet Model (IDM) \[10\], where a DM candidate coming from the doublet with Vacuum Expectation Value (VEV) equal to zero and its mass has been constrained to the order of GeV \[11, 12\]. Recently a two Higgs doublet model (2HDM) with a \(U(1)\) gauge symmetry, including a gauge boson \(Z'\) with mass of order of GeV scale or below, has been proposed, that is the case of the D2HDM \[13, 14\]. However, the word "Dark" in references \[13, 14\] is used due to the invisible light gauge boson.

In the D2HDM a continuous symmetry \(U(1)\) is the mechanism to keep very suppressed the Yukawa couplings between fermions and scalars, while in the IDM this is achieved by imposing a \(Z_2\) discrete symmetry. In this work we consider as starting point the D2HDM in order to propose a model with WIMP-like DM candidate particle.

### 2. The Inert Doublet Model-\(U(1)_X\)

The considered gauge group for the model is defined as \(G_{IDMU_X} = G_{SM} \otimes U(1)_X\) where \(G_{SM}\) is the gauge group symmetry of the SM. We name this model as Inert Doublet Model with \(U(1)_X\) (IDM-\(U(1)_X\)) and the coupling constant associated to \(U(1)_X\) is denoted as \(g_X\). From here on we will explain the scalar and gauge bosons sectors such that a dark matter candidate can be viable in the IDM-\(U(1)_X\).

#### 2.1. Scalar sector

The scalar sector in the IDM-\(U(1)_X\) contains two complex scalar doublets with hypercharge \(Y = 1\), which is the content of the IDM. One doublet plays the role of the doublet of the SM, meanwhile the second one is the inert doublet with null VEV. Usually, the particles with very little or no interaction are referred as inert particles. Additional to these two doublets, we consider one complex singlet scalar field \(\Phi_x\) with VEV denoted by \(v_x\). The singlet \(\Phi_x\) is introduced to break down the symmetry \(G_{IDMU_X}\) to the \(G_{SM}\). As it happens in SM, the doublet with non zero VEV is responsible for the spontaneous electroweak symmetry breaking.

The models with discrete symmetry, for instance the \(Z_2\) symmetry, are able to have an inert particle by imposing that its doublet is transformed in no trivial form under \(Z_2\). However, our proposal is based in the continuous symmetry \(U(1)_X\) instead of a discrete symmetry, which also can control interaction between neutral scalars and other particles. Scalar fields are denoted as \(\Phi_1\) and \(\Phi_2\) for doublets and \(\Phi_x\) for singlet, as previously introduced. These scalar fields have quantum number under \(G_{IDMU_X}\) defined as

\[
\Phi_1 \sim (1, 2, 1/2, x_1),
\]

and

\[
\Phi_2 \sim (1, 1, 1/2, x_2),
\]

\[
\Phi_x \sim (1, 1, 0, v_x).
\]
\[ \Phi_2 \sim (1, 2, 1/2, x_2), \]
\[ \Phi_x \sim (1, 1, 0, x), \]

where two first entries denote the representation under $SU(3)_C$ and $SU(2)_L$ meanwhile the hypercharge and charge $U(1)_X$ are written in the last two entries. Then, the most general, renormalizable and gauge invariant potential is

\[
V = \mu_1^2 \Phi_1^\dagger \Phi_1 + \mu_2^2 \Phi_2^\dagger \Phi_2 + \mu_x^2 \Phi_x^\dagger \Phi_x + \left[ \mu_{12}^2 \Phi_1^\dagger \Phi_2 + h.c. \right] \\
+ \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\
+ \lambda_4 (\Phi_1^\dagger \Phi_2)^2 + \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\
+ \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_1) + h.c.] + \lambda_x (\Phi_x^\dagger \Phi_x)^2 \\
+ (\Phi_x^\dagger \Phi_x) \left[ \lambda_{1x} (\Phi_1^\dagger \Phi_1) + \lambda_{2x} (\Phi_2^\dagger \Phi_2) \right] \\
+ \lambda_{12x} (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + h.c.] + \lambda_x' (\Phi_1^\dagger \Phi_1) \Phi_x \\
+ \lambda_x' (\Phi_2^\dagger \Phi_2) \Phi_x + \lambda_x' (\Phi_x^\dagger \Phi_x) \Phi_x + h.c.] . \tag{3}
\]

The $\mu_1^2, \mu_2^2, \mu_x^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_x, \lambda_{1x}, \lambda_{2x}$ are real parameters and the rest of the parameters are complex. The potential (3) is not only CP non conserving but it has terms involving odd power which do not allow the stability of the DM candidate, for instance the terms proportional to $\lambda_{12x}^2$ or $\lambda_x'^2$. We set the values of the $U(1)_X$ charges $x_1, x_2$ and $x$ in order to suppress the terms in the potential that do not allow the stability for DM candidate. In the potential the terms of the form $\Phi_1 \Phi_2$ are allowed by gauge invariance when the $U(1)_X$ charges satisfy $x_1 = x_2$. If $x_1 \neq x_2$, the parameters $\mu_{12}, \lambda_5$ and $\lambda_{12x}$ must be equal to zero in order to guarantee the gauge invariance. We also assume $x \neq 0$ in order to involve the singlet scalar in the $U(1)_X$ symmetry breaking mechanism. Therefore, the parameters $\lambda_x'^2$ and $\lambda_{12x}'^2$ must also be null to guarantee the gauge invariance. The term $\left( \Phi_1^\dagger \Phi_2 \right) \Phi_x$, which induces decay of the DM candidate, can be eliminated of the scalar potential if we assume $x_2 - x_1 \neq x$.

Under the last assumptions the scalar potential is simplified to

\[
V = \mu_1^2 \Phi_1^\dagger \Phi_1 + \mu_2^2 \Phi_2^\dagger \Phi_2 + \mu_x^2 \Phi_x^\dagger \Phi_x + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 \\
+ \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)^2 \\
+ \lambda_x (\Phi_x^\dagger \Phi_x)^2 + (\Phi_x^\dagger \Phi_x) \left[ \lambda_{1x} (\Phi_1^\dagger \Phi_1) + \lambda_{2x} (\Phi_2^\dagger \Phi_2) \right] . \tag{4}
\]

After spontaneous symmetry breaking, the scalar fields acquire VEV such that

\[
\langle \Phi_1 \rangle = \left( \begin{array}{c} 0 \\ v \end{array} \right) , \tag{5}
\]
\[
\langle \Phi_2 \rangle = \left( \begin{array}{c} 0 \\ 0 \end{array} \right) \tag{6}
\]
and

\[
\langle \Phi_x \rangle = \frac{v_x}{\sqrt{2}} . \tag{7}
\]

The masses of the physical scalars are

\[
M_{h_1}^2 = 2 \lambda_1 v^2 , \tag{8}
\]
$$M_{h_2,h_3}^2 = \mu_2 + \frac{1}{2} v^2 (\lambda_3 + \lambda_4) + \frac{1}{2} v_x^2 \lambda_x,$$

$$M_{H^\pm}^2 = \mu_2 + \frac{1}{2} v^2 \lambda_3 + \frac{1}{2} v_x^2 \lambda_x,$$

$$M_x^2 = 2 \lambda_x v_x^2.$$  

The extremal conditions for (4) are

$$2 \mu_1^2 + 2 \lambda_1 v_x^2 + \lambda_1 v_x^2 = 0 \quad (12)$$

and

$$2 \mu_2^2 + 2 \lambda_2 v_x^2 + \lambda_1 v_x^2 = 0.$$

In this case the mass matrix for neutral scalars is diagonal and there is degeneration in the masses of the neutral scalars $h_2$ and $h_3$ due to the non diagonal elements that could arise from the terms proportional to the parameters that were taken equal to zero. The $U(1)_X$ charges for scalars can be taken with values such as to generate this mixing between neutral scalars. However, the only combination that retains the stability of the neutral scalar from $\Phi_2$ is considered above, $(x_1, x_2, x_3) = (0, -x, x)$ with $x \neq 0$.

### 2.2. Gauge-scalar interactions

The interactions between the scalar and gauge bosons are given by

$$L_{\text{gauge-scalar}} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2 + |D_\mu \Phi_x|^2,$$

where the covariant derivative $D_\mu$ is defined as

$$D_\mu = \left( \partial_\mu + ig' Y \hat{B}_\mu + ig T_3 \hat{W}_3^{0 \mu} + ig Z' Q' \hat{Z}_0^{0 \mu} \right).$$

The hat notation in the vector bosons refers to states before a transformation is applied to eliminate the kinetic mixing between the $U(1)_Y$ and $U(1)_X$ tensor fields which is given by

$$L_{\text{Kinetic}} = -\frac{1}{4} \hat{B}^{\mu \nu} \hat{B}_{\mu \nu} + \frac{1}{2} \frac{\varepsilon}{\cos^2 \theta_W} \hat{B}^{\mu \nu} \hat{Z}'_{0 \mu \nu} - \frac{1}{4} \hat{Z}'_{0 \mu \nu} \hat{Z}'_{0 \mu \nu},$$

where $\hat{B}^{\mu \nu}$ and $\hat{Z}'_{0 \mu \nu}$ are the field strength tensors of the $U(1)_Y$ and $U(1)'$ gauge bosons, respectively. If the transformation

$$\begin{pmatrix} Z_{0 \mu} \\ B_\mu \end{pmatrix} \rightarrow \begin{pmatrix} \sqrt{1 - \varepsilon^2/\cos^2 \theta_W} & 0 \\ -\varepsilon/\cos^2 \theta_W & 1 \end{pmatrix} \begin{pmatrix} \hat{Z}'_{0 \mu} \\ \hat{B}_\mu \end{pmatrix}$$

is applied, the kinetic term with mixing in (16) is removed. The transformation is also applied in (14) and after spontaneous symmetry breaking this Lagrangian is written as

$$L = L_{\text{masses}} + L_{\text{interactions}},$$

where

$$L_{\text{masses}} = \frac{1}{2} m_{Z'0}^2 Z'^0 Z'^0 + \frac{1}{2} m_{Z'0}^2 Z'^0 Z'^0 - \Delta^2 Z'^0 Z^0 + ...$$

with

$$m_{Z'0}^2 = \frac{1}{4} \theta Z'^0 Z'^0,$$
\begin{align}
m^2_{Z^0} & = g_x^2 (v^2 + v_x^2) + \frac{\epsilon}{\cos \theta_W} g_x g^2 + \frac{1}{4} \left( \frac{\epsilon}{\cos \theta_W} \right)^2 g^2 v^2, \\
\Delta^2 & = \frac{1}{2} g_x g_Z v^2 + \frac{1}{4 \cos \theta_W} g_Z g'^2.
\end{align}

Additionally to the mass terms for the gauge bosons, the mixing term \((Z_0 \mu_{Z^0})\) appears. This mixing term can be eliminated through the following rotation

\begin{align}
\begin{pmatrix}
Z \\
Z'
\end{pmatrix}
& =
\begin{pmatrix}
\cos \xi & -\sin \xi \\
\sin \xi & \cos \xi
\end{pmatrix}
\begin{pmatrix}
Z_0 \\
Z'^0
\end{pmatrix},
\end{align}

where the mixing angle \(\xi\) satisfies the expression \(\tan 2\xi = \frac{2\Delta^2}{m_{Z^0}^2 - m_{Z^0}'}\), and has been constrained to \(|\xi| < 10^{-3}\) \([15]\). The detailed description for \(\mathcal{L}_{\text{interactions}}\) can be reviewed in references \([13, 14]\).

3. Discussion

We considered a model with new particles that arise though extending the scalar sector and a neutral gauge boson from the additional symmetry \(U(1)_X\). The mass spectrum for these neutral scalar and gauge bosons was presented in Eq. (9) and Eq. (21). These equations show the importance of the free parameters \(\lambda_X, v_X\). The model presents a degeneration in the masses of the neutral scalars \(h_{2,3}\) due to the elimination of the parameter \(\lambda_5\). The \(\lambda_5\) coupling must vanish to guarantee the gauge invariance when the values of \(x\) were restricted in order to control the interactions. This means that the model can provide a scenario for two dark matter candidates with degenerate masses. Other scenario where the DM candidate is identified with the singlet in a model with additional symmetry \(U(1)\) was studied previously \([16]\). The next step is to take into account the limits reported for observable quantities involving these new particles.

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