Strongly First-Order Phase Transition in Real Singlet Scalar Dark Matter Model

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The extension of the standard model by a real gauge singlet scalar is the simplest but the most studied model with sometimes controversial ideas on the ability of the model to address the dark matter and the electroweak phase transition issues separately or simultaneously. For this model, we obtain analytically the condition for strongly first-order electroweak phase transition and apply that in computation of the dark matter relic density where the real scalar plays the role of the dark matter particle. Despite some previous results in the literature, we show that the scalar in this model can be responsible for all or part of the dark matter abundance, while at the same time gives rise to a strongly first-order electroweak phase transition required for the baryogenesis. When the constraint from the recent direct detection experiments such as LUX/XENON1t is considered the model is closely excluded. If the XENON100 bound is considered, the viable dark matter mass is in the range 80 – 250 GeV.

I. INTRODUCTION

Apart from the discovery of the Higgs particle - the last elementary particle and the first scalar discovered in Nature- at the Large Hadron Collider (LHC) [1, 2], the search for a footprint of beyond the Standard Model (BSM) of elementary particles by the experiments at the LHC has ended up to null results so far [3]. However, there are strong motivations to look for beyond the standard model. Some examples are the unknown mechanism of the electroweak symmetry breaking (see [4] for a review), the matter-antimatter asymmetry observed today in the Universe, and the mystery of the dark matter (DM), which in all cases the existence of at least one more degree of freedom in the SM seems inevitable. On the other hand, the Higgs might not be the only scalar field in Nature and the existence of further scalar degrees of freedom is not unlikely. The first possible addition of such a scalar would be the standard model (SM) plus a gauge-singlet scalar field. This is the simplest model beyond the standard model and has been studied vastly from various aspects in the past; two main categories of these investigations may be classified as when the scalar field is stable and enjoys a vacuum expectation value (vev) of the singlet scalar is not required. In the most recent work on the status of the singlet scalar dark matter by the GAMBIT collaboration [34], the Bayesian and frequentist global fits on the nuisance parameters of the model after imposing the constraints from the Planck for the relic density, the LUX, PandaX, SuperCDMS, XENON100 in direct searches, the invisible Higgs decay at the LHC, the IceCube for the DM annihilation to high energy neutrinos in the Sun, and the Fermi-LAT for DM annihilation into gamma rays in dwarf galaxies, show that the viable DM mass in the singlet scalar model sits either in the range $125 – 300$ GeV or is about $1$ TeV if the scalar constitutes all the dark matter. A global fit of the $\gamma$-ray galactic center excess in the real singlet scalar dark matter model is accomplished in Ref. [35].

There are a few works that have addressed both the DM and the EWPT in the singlet scalar model [36–41]. For instance, Refs. [40] report the inability of the model to account for both DM relic abundance through the freeze-out mechanism and the first-order EWPT. Also in Ref. [37] it is argued that only if the scalar constitutes 3% of the dark matter relic abundance then the model could lead to the first-order phase transition while evading the XENON100 direct detection bound.

We update as well the direct detection constraint to the recent results from LUX and XENON1t. Our results will be in agreement with the recent report of the GAMBIT collaboration but in contrast partially with previous sim-
ilar works discussing both the DM and the EWPT.

The paper is organized as the following. In the next section we recall the model and obtain analytically the washout criterion for the electroweak phase transition, then in section III we compute the dark matter relic density and the DM-nucleon cross section while imposing the strongly first-order phase transition. We conclude with section IV.

II. FIRST-ORDER PHASE TRANSITION

The model is the simplest renormalizable extension of the SM with an additional real singlet scalar that we denote it here by $s$. The real scalar $s$ interacts with the SM through only the Higgs portal having a quadratic interaction with the Higgs particle. Therefore beside the Higgs and the scalar potentials,

$$V_H = -\mu_H^2 H\dagger H + \lambda_H (H\dagger H)^2$$
$$V_s = -\mu_s^2 s^2 + \lambda_s s^4,$$

the total potential includes also the interaction part,

$$V_{\text{int}} = \lambda_{hs} s^2 H\dagger H,$$

where $H$ denotes the Higgs $SU(2)$ doublet and $\lambda_{hs}$ is the scalar-Higgs interaction coupling playing an important role in our analysis. There are only two free parameters in the model i.e. the scalar mass and the coupling, $\lambda_{hs}$. Notice that we are not considering the odd powers of the real scalar $s$, in the potential so as to respect the $Z_2$ discrete symmetry on $s$, such that the scalar could be representative of a stable dark matter particle in the so-called freeze-out mechanism. Gauging away three components of the Higgs doublet, only one real component, $h$, is remained and the Higgs in eqs. (1) and (2) can be replaced by $H = \sqrt{2}(0 + v_h)$ after the electroweak symmetry breaking. When the temperature is very high the theory consisting of the SM and the new real scalar, lives in its symmetric phase. In this stage, the Higgs takes zero vacuum expectation value while the scalar could have zero or non-zero $vev$. The tree-level total potential at high temperature can then be written as,

$$V_{\text{tr}}(h, s) = -\frac{1}{2}\mu_h^2 h^2 - \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_s s^4 + \frac{1}{2}\lambda_{hs}s^2 h^2.$$

As the Universe cools down, at the time of electroweak symmetry breaking at lower temperatures, we assume a one-step phase transition so that the $vev$s of the scalars, $h$ and $s$, change from $(v_h = 0, w_s = 0)$ to $(v \neq 0, w = 0)$ at temperature $T_c$ where $v \equiv (h)$ and $w \equiv (s)$. We require that after the phase transition $w = 0$ because otherwise the $Z_2$ symmetry is broken and the scalar $s$ can no longer be taken as the dark matter candidate.

Along the lines of [31], in addition to the tree-level barrier we include also the one-loop thermal potential in order to get a strong EWPT,

$$V_{1\text{-loop}}(h, s; T) \simeq \left(\frac{1}{2}c_h h^2 + \frac{1}{2}c_s s^2\right)T^2,$$

where the parameters $c_h$ and $c_s$ are the following,

$$c_h = \frac{1}{48}(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + 2\lambda_{hs})$$
$$c_s = \frac{1}{12}(4\lambda_{hs} + 3\lambda_s).$$

The one-loop correction at zero-temperature in the effective potential as pointed out in [12] is negligible, therefore the thermal one-loop effective potential can approximately be written as,

$$V_{\text{eff}}(h, s; T) = V_{\text{tr}}(h, s) + V_{1\text{-loop}}(h, s; T).$$

The critical temperature $T_c$ of the electroweak phase transition, is the temperature at which the free energy (thermal effective potential in eq. (6)) in the symmetric phase equals the free energy in the broken phase. In other words, the thermal effective potential gets two degenerate minima at $T = T_c$. Note the fact that we deal with two types of symmetries here. One is the $Z_2$ discrete symmetry in $s$ which must exist lower the freeze-out temperature, $T_f$ and the other is the $SU(2)$ electroweak symmetry which holds in high temperatures. The phase transition process we consider here is a transition from $(h, s) = (v_{\text{sym}} = 0, w_{\text{brk}})$ to $(h, s) = (v_{\text{brk}}, w_{\text{sym}} = 0)$. We recall that at high temperatures the scalar field $s$ can always have non-zero vacuum expectation value. The minima of the thermal effective potential in eq. (6) read,

$$v_{\text{sym}} = 0 \quad \text{or} \quad v_{\text{brk}}^2(T) = \frac{\mu_h^2 - c_h T^2}{\lambda_h},$$

where $v_{\text{brk}}$ is the $T$-dependent Higgs $vev$, and

$$w_{\text{sym}} = 0 \quad \text{or} \quad w_{\text{brk}}^2(T) = \frac{\mu_s^2 - c_s T^2}{\lambda_s},$$

with $w_{\text{brk}}$ being the $T$-dependent $vev$ of the scalar $s$.

Now the critical temperature at which the transition from $(v_{\text{sym}} = 0, w_{\text{brk}})$ to $(v_{\text{brk}}, w_{\text{sym}} = 0)$ takes place is obtained by solving $V_{\text{eff}}(0, w_{\text{brk}}; T_c) = V_{\text{eff}}(v_{\text{brk}}, 0; T_c)$. The answer can be expressed as,

$$T_c^\pm = \sqrt{\frac{a \pm b}{c}},$$

Note that in the early Universe, the dark matter freezes out from the plasma of particles in a temperature much lower than the electroweak phase transition temperature, $T_c$. Therefore it only suffices that the real scalar takes zero $vev$ just above the freeze-out temperature, $T_f$. 

\[1\]
we have therefore two conditions, 

\[ \begin{align*}
\lambda_v &= \mu^2_c c_h \lambda_h - \mu^2_h c_h \lambda_s , \\
b &= |\mu^2_c c_h - \mu^2_h c_h| \sqrt{\lambda_h \lambda_s} , \\
c &= c_s \lambda_h - c_h \lambda_s .
\end{align*} \tag{10} \]

As seen from eq. (9) for each set of the independent parameters, there are two solutions for the degeneracy of the minima in the free energy which are denoted by \( T^+_c \) and \( T^-_c \). We explore both cases when we study the scalar as a dark matter candidate in the next section.

One of the Sakharov’s conditions for the baryon asymmetry is guaranteed by the suppressed sphaleron rate in the Higgs broken phase. This is equivalent to the condition \( v_c / T_c > 1 \) that is called the washout criterion in which \( \nu_c \equiv v_{\text{dark}}(T) \). For the solutions we found in eq. (11), we have therefore two conditions,

\[ \frac{v^\pm_c (T_c)}{T^\pm_c} > 1 , \tag{11} \]

where \( v^\pm_c \) is given by,

\[ v^\pm_c = \frac{c_s \mu^2_h c_h \mu^2_c}{c_s \lambda_h \pm c_h \lambda_s}. \tag{12} \]

The stability conditions at \( T = 0 \) reduce the number of the independent parameters. The Higgs physical mass fixes the parameter \( \mu^2_h \) as \( \mu^2_h = m^2_H / 2 \) with \( m_H = 125 \text{ GeV} \). The Higgs quartic coupling is also fixed as \( \lambda_h = m^2_{H}/2v^2_{h} \approx 0.129 \). Then from eq. (10), \( \lambda_s > 0 \). The physical mass of the scalar \( s \) (dark matter mass) is given by \( m_{DM}^2 = m^2_s - \mu^2_h \lambda_s v^2_H \). The positivity of the dark matter mass then requires \( \mu^2_s < \lambda_h v^2_H \).

III. DARK MATTER

Another important issue we take into account in the simple model of the real scalar extension of the SM is the problem of the dark matter. Because of the \( \mathbb{Z}_2 \) discrete symmetry on the scalar \( s \) we considered in the model in eq. (3), the scalar is stable and is taken as the weakly interacting massive particle (WIMP). The DM particle is in thermal equilibrium with the SM particles in the early Universe but it detaches from the other particles at the freeze-out temperature, \( T_f \) after the Universe is expanded enough with the Hubble rate. The \( vev \) of the Higgs particle at the freeze-out temperature (after the electroweak phase transition) is \( v_h = 246 \text{ GeV} \) and that of the scalar is \( v_s = 0 \) so there is no mixing between the Higgs and the DM particle. Therefore, the only annihilation channel we deal with is \( ss \rightarrow \text{Higgs} \rightarrow \text{SM} \). The only independent coupling in the Lagrangian that enters in the dark matter annihilation process and the dark matter elastic scattering off the nuclei is the \( \lambda_{hs} \) in eq. (3). The other parameters in the theory does not affect the computation of the relic density and the elastic scattering cross section. Nevertheless, they will of course participate in the EWPT restrictions. In our computations, we confirm that in a temperature much lower than the electroweak phase transition temperature, the dark matter freezes out from of the thermal equilibrium. This means that at the time of freeze-out the Higgs is already in its current vacuum expectation value or equivalently the theory is in its broken phase for the SU(2) symmetry of the SM and in its symmetric phase for the \( \mathbb{Z}_2 \) symmetry of the dark sector.

The time evolution of the dark matter density is obtained by solving the Boltzmann differential equation,

\[ \frac{d n_s}{d t} = -3H n_s - \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle \left[ n_s^2 - \langle n_s^2 \rangle \right] , \tag{13} \]

where \( H \) stands for the Hubble expansion rate of the Universe (not to be confused with the Higgs doublet denoted in section II), \( \sigma_{\text{ann}} \) is the dark matter annihilation cross section, \( v_{\text{rel}} \) is the dark matter relative velocity and the bracket means the thermal average. Exploiting the micrOMEGAs 4.3.5 package \cite{Belanger:2018}. we obtained the relic...
FIG. 3. The DM mass against the DM-nucleon cross section when the electroweak phase transition is strongly first-order and upper plot) the singlet scalar constitutes 0 – 100% of the total DM relic density $\Omega_{DM} h^2 \sim 0.12$ and lower plot) the singlet scalar constitutes 80 – 100% of the total DM relic density. While the XENON100 cross section bound allows a DM mass 80 – 250 GeV with 100% contribution of the relic density, the model is excluded closely by XENON1t limit.

density by solving numerically the Boltzmann differential equation in eq. [13]. Having applied the stability conditions, we scanned over all DM masses in the range 10 GeV–10 TeV while the only relevant coupling $\lambda_{hs}$ being in the interval $-2 < \lambda_{hs} < 2$. The result is demonstrated in Fig. 1. As seen in the plot, the dark matter particle, $s$, enjoys a viable space of the coupling $\lambda_{hs}$ to account for all the relic abundance observed in the Universe by WMAP/Planck [44, 45] to be $\Omega_{DM} h^2 \sim 0.12$. Furthermore, we observe from this figure that the coupling $\lambda_{hs}$ has a descending behavior from heavier DM mass to lighter ones. This behavior changes at the resonance i.e. at $m_s \equiv m_{DM} = m_h/2$.

To calculate the DM-nuclei elastic scattering cross section, there is only one $t$-channel $s\bar{s}q\bar{q}$ Feynman diagram which can be easily read from the vertices. However, one needs to use the effective operator for the interaction $s\bar{s}NN$ which requires the use of the nucleon form factors. The DM-nucleon spin-independent elastic scattering cross section is the following,

$$\sigma_{SI}^N = \frac{\alpha_N^2 \mu_N^2}{\pi m_{DM}^2} \quad (14)$$

where $\alpha_N$ is the effective coupling given in terms of the form factors and $\mu_N$ is the DM nucleus reduced mass (see e.g. [46] for more details). The DM-nucleon cross section can also be computed in the micrOMEGAs4.3.5 package. For each set of the parameters that lead to the correct dark matter relic abundance, we have computed the scattering cross section. The result in Fig. 2 shows that the cross section saturates the LUX bound [47] at $\sim m_s \equiv m_{DM} \sim 350$ GeV and the XENON1t limit [48] at $\sim m_{DM} \sim 600$ GeV and of course for the resonance region. We do not focus on the resonance region because it is excluded when we add the washout criterion into our computation as comes latter on. We therefore conservatively can exclude the DM mass to be $m_{DM} \gtrsim 600$ GeV if only the total relic density and the direct detection bounds are taken into consideration. This is consistent with the results in Ref. [34] suggesting a viable DM mass of order $\sim 1$ TeV. Note that we have not considered all the constraints in Ref. [34] that is why the viable DM mass seen in Fig. 2 has only a lower bound. In Fig. 1 the coupling is of order of one as has been mentioned in the results of the GAMBIT global fit [34].

We finally take into account the first-order phase transition condition (washout criterion) obtained in eqs. [9] and [11]. Our first result which is in conflict with some previous claims in the literature (e.g. [40]) is that the singlet scalar can be responsible for 100% of the dark matter relic density and the strongly first-order electroweak phase transition at the same time. In our computations the strongly first-order EWPT condition is applied on the space of the parameters where the singlet scalar can account for the dark matter from 0 to 100 percent of the total DM relic density in the Universe. In Fig. 3 the spin-independent DM-nucleon cross section against the DM mass is plotted when the singlet scalar takes $0 \sim 100\%$ and once it takes $80 \sim 100\%$ of the dark matter relic density. As seen in this figure, the singlet scalar could take any percentage of the DM including the total amount of that while fulfilling the strongly first-order electroweak phase transition. However, the DM-nucleon cross section increases when the percentage of the DM relic density decreases. If the elastic scattering cross section limit by XENON100 is imposed, we observe in Fig. 3 that there are viable space that evades this constraint when the singlet scalar constitutes $80 \sim 100\%$ of the DM relic density which is in conflict with the results in Ref. [37]. In fact, it is seen promptly from Fig. 3 that the less percent of the DM the singlet scalar takes, the most it is excluded by the XENON100 limit. When the singlet scalar takes $80 \sim 100\%$ of the DM abundance or even the entire relic density, the DM-nucleon cross section although is excluded by the latest direct detection experiments i.e. the XENON1t/LUX, but it is very close to the exclusion lines (see the lower plot in Fig. 2). The
DM mass which is not excluded by the XENON100 and the singlet scalar constitutes all the DM content in the Universe while giving rise to a strongly first-order phase transition in the range $80 - 250$ GeV.

IV. CONCLUSION

In this article we have studied the real singlet scalar dark matter model with only two additional parameters compared to the SM. The extra scalar in the model is used to simultaneously play the role of the dark matter particle and make the electroweak phase transition strongly first-order. We have shown that despite the previous results in the literature this model is capable of explaining partially or entirely the dark matter relic abundance in the Universe measured by the WMAP/Planck, and the electroweak phase transition to be strongly first-order while taking into account the DM-nucleon elastic scattering cross section bound given by the LUX/XENON100/XENON1t experiments. The model is closely excluded by the XENON1t experiment but if considering the XENON100 limit, the viable DM mass is in the range $80 - 250$ GeV.

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