Spontaneous electro-weak symmetry breaking and cold dark matter

Shou-hua Zhu
Institute of Theoretical Physics, School of Physics, Peking University, Beijing 100871, China
(Dated: February 24, 2022)

In the standard model, the weak gauge bosons and fermions obtain mass after spontaneous electro-weak symmetry breaking, which is realized through one fundamental scalar field, namely Higgs field. In this paper we study the simplest scalar cold dark matter model in which the scalar cold dark matter also obtains mass through interaction with the weak-doublet Higgs field, the same way as those of weak gauge bosons and fermions. Our study shows that the correct cold dark matter relic abundance within 3σ uncertainty (0.093 < Ω_{dm} h^2 < 0.129) and experimentally allowed Higgs boson mass (114.4 ≤ m_h ≤ 208 GeV) constrain the scalar dark matter mass within 48 ≤ m_S ≤ 78 GeV.

This result is in excellent agreement with that of W. de Boer et.al. (50 ≲ 100 GeV). Such kind of dark matter annihilation can account for the observed gamma rays excess (10σ) at EGRET for energies above 1 GeV in comparison with the expectations from conventional Galactic models. We also investigate other phenomenological consequences of this model. For example, the Higgs boson decays dominantly into scalar dark matter if its mass lies within 48 ≲ 64 GeV.

PACS numbers: 14.80.-j, 14.60.Pq, 11.15.Ex

Understanding the mechanism of electro-weak symmetry breaking (EWSB) is a primary goal of the Large Hadron Collider (LHC) and International Linear Collider (ILC). In the standard model (SM), EWSB is realized through one fundamental Higgs field, namely the vacuum expectation value (VEV) of Higgs field < Φ > ≠ 0. After EWSB the weak gauge bosons and fermions obtain mass, and only one neutral Higgs boson is left in particle spectrum. The couplings among Higgs boson and weak gauge bosons/fermions are proportional to their corresponding mass. This is one of the most important features of spontaneous EWSB. Though this feature has not been directly tested in the past experiments, the SM predictions of cold dark matter relic density in Eq. (1) and experimentally allowed Higgs boson mass are in excellent agreement with the expectations from conventional Galactic models. We also investigate other phenomenological consequences of this model. For example, the Higgs boson mass lies within 48 ≲ 64 GeV.

0.093 < Ω_{dm} h^2 < 0.129 (1)

where h ≈ 0.71 is the normalized Hubble expansion rate. However the microscopic properties of dark matter are remarkably unconstrained. Therefore it is quite interesting to ask how cold dark matter interacts with usual SM matter. Though the cold dark matter is allowed to feel weak interaction, such possibility will usually involve more free parameters. The popular cold dark matter candidate neutralino in supersymmetrical models is a good example. Therefore in this paper we only discuss the case that dark matter is SM gauge group singlet.

Motivated by the successful assumption that weak gauge bosons and fermions obtain mass from the interactions with weak-doublet Higgs field, it is quite natural to assume that SM gauge group singlet cold dark matter obtains mass the same way as those of weak gauge bosons and fermions. Thus the coupling among Higgs boson and cold dark matter is solely fixed by dark matter mass. If the dark matter is fermion, it will obtain mass through dimension-five non-renormalizeble operator (iγµγ5Φ)(Φ†Φ) with Φ the usual weak-doublet Higgs field. Thus we prefer to take the cold dark matter as scalar field, denoted as S. In fact the scalar particle as cold dark matter has been widely studied in literature [4, 5]. If we introduce only one singlet scalar field S, there is only one extra free parameter other than those in the SM, namely the mass of the scalar cold dark matter m_S. In this paper we will study this simplest cold scalar dark matter model. Our results show that the correct cold dark matter relic density in Eq. (1) and experimentally allowed Higgs boson mass (114.4 ≤ m_h ≤ 208 GeV) constrain the scalar dark matter within 48 ≤ m_S ≤ 78 GeV. This result is in excellent agreement with that of W. de Boer et.al. (50 ≲ 100 GeV) [6]. Such kind of dark matter annihilation can account for the observed gamma rays excess (10σ) at EGRET for energies above 1 GeV in comparison with the expectations from conventional Galactic models. In this paper we also investigate other phenomenological consequences of this model. For example, the Higgs boson decays dominantly into scalar cold dark matter if its mass lies within 48 ≲ 64 GeV.

The Lagrangian of the simplest model can be written as

\[ L = L_{SM} + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{\lambda_S}{4} S^4 - \lambda S^2 (\Phi^+ \Phi) \]  (2)

where \( L_{SM} \) is the Lagrangian of the SM and \( \Phi \) is the weak doublet Higgs field. \( L \) is obviously invariant un-
under discrete transformation $S \rightarrow -S$, which ensures $S$ the good candidate of cold dark matter. The model discussed in this paper is different from that of Ref. [2]. The main difference is that the mass term of $S$ field $m_0^2 S^2$ is not included in this paper. It is known that the mass of dark matter can vary many orders of magnitude depending on the strength it interacts with usual matter. Here we investigate the possibility that dark matter is in the weak scale while $m_0^2$ can be anything. Therefore it is unnecessary to introduce one extra new mass scale. In this paper we assume that weak doublet Higgs field solely induces mass for all particles: weak gauge bosons, fermions and singlet scalar field $S$. The model can be a massless one before EWSB. The spontaneous symmetry breaking, trigger by $\mu^2 \Phi^\dagger \Phi$, can be induced radiatively [2]. On the contrary $S^2$ term is absent or negligibly small provided that it does not get contribution from $\lambda S^2 (\Phi^\dagger \Phi)$. After spontaneous electro-weak symmetry breaking $< \Phi > = v = 246$ GeV, the Higgs boson, as in the standard model, $m_h^2 = \lambda v^2$ with $\lambda_h$ the coefficient of $(\Phi^\dagger \Phi)^2$ and $m_S^2 = \lambda v^2$. It is obvious that coupling $\lambda$ is determined by $m_S$ and in this model $\lambda$ is the only extra free parameter relevant to our discussion.

Next we will explore the cosmological constraints on this model by demanding the present abundance of $S$ to be in the range of Eq. (1). As we can see, this imposes a very strong relationship between Higgs boson mass and $m_S$. The calculation of $S$ abundance follows the standard procedure [5] and we refer the interesting reader to Ref. [6] for the details.

The present density of $S$ can be written as [3]

$$\Omega_S h^2 = \frac{1.07 \times 10^9 x_f}{\sqrt{g_* M_{pl} \text{[in GeV]} < \sigma v_{rel} >}},$$  \hspace{1cm} (3)

where $g_*$ counts the degrees of freedom in equilibrium at annihilation, $x_f$ is the inverse freeze-out temperature in units of $m_S$, which can be obtained by solving the equation

$$x_f \simeq \ln \left[ \frac{0.038 M_{pl} m_S < \sigma v_{rel} >}{\sqrt{g_* x_f}} \right].$$  \hspace{1cm} (4)

In Eqs. (3) and (4), $v_{rel}$ is the relative velocity of the two incoming dark matter particles, $M_{pl}$ is the Planck mass and $< ... >$ denotes the relevant thermal average.

Since the scalar dark matter obtains mass through interaction with VEV of the Higgs field, it is natural to expect that dark matter mass scale is $O(100)$ GeV. Therefore $\sigma v_{rel}$ can be obtained by evaluating the tree-level diagram in Fig. 1. In the non-relativistic limit, $\sigma v_{rel}$ is [7]

$$\sigma_{ann} v_{rel} = \frac{8 \lambda^2 v^2}{(4 m_S^2 - m_h^2)^2 + m_h^2 \Gamma_h^2} F_X$$

$$= \frac{8 |m_S^2|}{v^2 (4 m_S^2 - m_h^2)^2 + m_h^2 \Gamma_h^2} F_X$$  \hspace{1cm} (5)

where $F_X = \lim_{m_h \rightarrow 2 m_S} \left( \frac{\Gamma_{h \rightarrow X}}{m_h} \right)$.

Here $\Gamma_h$ is the Higgs total decay width and $\Gamma_{h \rightarrow X}$ denotes the partial decay width for the virtual $h$ decay into $X$, $\tilde{h} \rightarrow X$, in the limit $m_h \rightarrow 2 m_S$. Here $X$ represents SM particles.

In Fig. 2 and table I we show the allowed Higgs boson and scalar dark matter mass region (between two curves). This mass region can produce correct relic density $0.093 < \Omega_{dm} h^2 < 0.129$ (within $3\sigma$ uncertainty). Also shown are Higgs boson upper (208 GeV) and lower (114.4 GeV) mass limits from electro-weak precision data global fit and direct search at LEP.

In Fig. 2 and table I we show the allowed Higgs boson and scalar dark matter mass region [between two curves], provided that relic abundance satisfies Eq. (1). From figure we can see a very strong relationship between Higgs boson mass and $m_S$. It is known that the
coupling strength among Higgs boson and SM particles is proportional to their corresponding mass, as we discussed above. At the same time, the coupling between Higgs boson and scalar dark matter is also proportional to \( m_S \). Once \( m_S \) is fixed, the only free varying parameter is \( m_h \). If we impose the Higgs mass constraints from direct search limit 114.4 GeV to 208 GeV, the allowed scalar dark matter is

\[
48 \leq m_S \leq 78 \text{ GeV.} \tag{7}
\]

It should be noted that \( m_S \) can’t be larger than \( m_W \). Otherwise the cross section of \( SS \rightarrow WW \) becomes too large and the relic abundance is out of the region in Eq. (1). Eq. (7) is in excellent agreement with that of W. de Boer et.al. (50) Eq. (7) is in excellent agreement with that of W. de Boer et.al. (50) Eq. (7) is in excellent agreement with that of W. de Boer et.al. (50) with \( \sim 100 \text{ GeV} \) \[4\]. Such kind of dark matter annihilation produces mono-energetic quarks of \( 50 \sim 100 \text{ GeV} \), which can account for the observed gamma rays excess (10\(\sigma \)) at EGRET for energies above 1 GeV in comparison with the expectations from conventional Galactic models. It should be emphasized that the crucial part of EGRET photon excess origin is mono-energetic quarks, no matter which kind of dark matter annihilation produces them. In fact the further investigation by W. de Boer et.al. \[9\] shows that supersymmetric models with \( |1+6x+4x^2| \log x \tag{9}
\]

with \( x = m_V^2/(4m_S^2) \).

\[
\begin{array}{c|c|c|c}
 m_S [\text{GeV}] & m_h \text{ upper limit [GeV]} & m_h \text{ lower limit [GeV]} \\
 50 & 122 & 119 \\
 55 & 134 & 131 \\
 60 & 148 & 144 \\
 65 & 162 & 158 \\
 70 & 180 & 174 \\
 75 & 204 & 197 \\
 80 & 275 & 261 \\
\end{array}
\]

TABLE I: Upper and lower limits on Higgs boson for several \( m_S \) in order to obtain the correct relic abundance in Eq. (1).

\[ \Gamma(h \rightarrow SS) = \frac{m_S^4}{8\pi v^2 m_h} \sqrt{1 - \frac{4m_S^2}{m_h^2}}. \tag{10} \]

\( \Gamma(h \rightarrow SS) \) and \( Br(h \rightarrow SS) \) are shown in Fig. \[3\] and \[4\] From Fig. \[3\] we can see that the partial decay width is between 0.02 \( \sim 0.08 \) GeV for \( m_S = 48 \sim 78 \text{ GeV} \). In Fig. \[4\] the rapid drop around \( m_S = 65 \text{ GeV} \) is due to the rapid growth of \( \Gamma(H \rightarrow VV^*) \). From Fig. \[4\] we can see good and bad news. The good news is that there is certain possibility that Higgs boson can decay into SM particle, especially for \( m_S \geq 64 \text{ GeV} \). Therefore we still have opportunity to see Higgs boson resonance as the case in the SM. The bad news is that we need more luminosity for the usual Higgs search strategies, especially for \( m_S \leq 60 \text{ GeV} \). Further efforts should be put on search of the invisibly Higgs boson decay \[11\].

In this paper we study the simplest scalar cold dark matter model in which the scalar cold dark matter obtains mass through interaction with the weak-doublet Higgs field, the same way as those of weak gauge bosons and fermions. The coupling between Higgs boson and scalar dark matter is solely fixed by scalar dark matter mass. The correct cold dark matter relic abundance within \( 3\sigma \) uncertainty \( (0.093 < \Omega_{dm}h^2 < 0.129) \) and experimentally allowed Higgs boson mass \( (114.4 \leq m_h \leq 208 \text{ GeV}) \) constrain the scalar dark matter mass within \( 48 \leq m_S \leq 78 \text{ GeV} \). This result is in excellent agreement with that of W. de Boer et.al. (50 \( \sim 100 \text{ GeV} \). Such
kind of dark matter annihilation can account for the observed gamma rays excess (10σ) at EGRET for energies above 1 GeV in comparison with the expectations from conventional Galactic models. We also investigate other phenomenological consequences of this model. Most importantly the Higgs boson decays dominantly into scalar cold dark matter if its mass lies within 48 ∼ 64 GeV.

Recently Bergstrom et. al. [12] investigated the internal consistency of the halo dark matter model which has been proposed by de Boer et. al. Certain inconsistency is found [12]. Now that the proposal of de Boer et. al. is still in debate, we should emphasize that our main results, i.e. (1) the correlation between masses of scalar dark matter and Higgs boson, (2) the Higgs boson can decay into dark matter with large branching ratio, might be irrelevant to the EGRET data. However LHC/ILC can provide ideal place to investigate the scalar dark matter in the Higgs boson decay [11].

Acknowledgements: The author thanks Prof. Y.Q. Ma for the discussion on EGRET, and Prof. C. Liu and H.Q. Zheng for the discussion on Eq. (2). This work was supported in part by the Natural Sciences Foundation of China under grant No. 90403004, the trans-century fund and the key grant project (under No. 305001) of Chinese Ministry of Education.

[1] A. Juste, arXiv:hep-ex/0511025.
[2] R. Barate et al. [LEP Working Group for Higgs boson searches], Phys. Lett. B 565, 61 (2003).
[3] S. Eidelman et al. [Particle Data Group], Phys. Lett. B 592 (2004) 1.
[4] M. J. G. Veltman and F. J. Yndurain, Nucl. Phys. B 325, 1 (1989); V. Silveira and A. Zee, Phys. Lett. B 161, 136 (1985); J. McDonald, Phys. Rev. D 50, 3637 (1994). H. Davoudiasl, R. Kitano, T. Li and H. Murayama, Phys. Lett. B 609, 117 (2005).
[5] C. P. Burgess, M. Pospelov and T. ter Veldhuis, Nucl. Phys. B 619, 709 (2001) arXiv:hep-ph/0011335.
[6] W. de Boer, C. Sander, A. V. Gladyshev and D. I. Kazakov arXiv:astro-ph/0508617.
[7] S. R. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973).
[8] E.W. Kolb and M.S. Turner, The Early Universe, Addison-Wesley, 1990.
[9] W. de Boer, C. Sander, V. Zhukov, A. V. Gladyshev and D. I. Kazakov, arXiv:hep-ph/0511154.
[10] A. Djouadi, arXiv:hep-ph/0503172 and references therein.
[11] S. h. Zhu, Eur. Phys. J. C 47, 833 (2006) arXiv:hep-ph/0512055 and references therein.
[12] L. Bergstrom, J. Edsjo, M. Gustafsson and P. Salati, JCAP 0605, 006 (2006) arXiv:astro-ph/0602632, for the earlier investigations to see, for example, A. Cesarini, F. Fucito, A. Lionetto and P. Ullio, Astropart. Phys. 21, 267 (2004) arXiv:nastro-ph/0305075; L. Bergstrom, P. Ullio and J. H. Buckley, Astropart. Phys. 9, 137 (1998) arXiv:nastro-ph/9712318; A. Bottino, F. Donato, N. Fornengo and S. Scopel, Phys. Rev. D 70, 015005 (2004) arXiv:hep-ph/0401186.
[13] Because the singlet scalar only interacts with Higgs boson, current electroweak precision data is not sensitive to such kind of new interactions beyond the SM. Therefore we assume that experimentally allowed Higgs boson mass in the SM is not affected.