Singlet fermionic dark matter as a natural higgs portal model \(^{123}\)

Kang Young Lee\(^*\), Yeong Gyun Kim\(^†\) and Seodong Shin\(^†\)

\(^*\)Department of Physics, Korea University, Seoul 136-701, Korea

\(^†\)Department of Physics, KAIST, Daejeon 305-701, Korea

Abstract. We propose a renormalizable model of a fermionic dark matter by introducing a gauge singlet Dirac fermion and a real singlet scalar. The bridges between the singlet sector and the standard model sector are only the singlet scalar interaction terms with the standard model Higgs field. The singlet fermion couples to the standard model particles through the mixing between the standard model Higgs and singlet scalar and is naturally a weakly interacting massive particle (WIMP). The measured relic abundance can be explained by the singlet fermionic dark matter as the WIMP within this model. Collider implication of the singlet fermionic dark matter is also discussed. Predicted is the elastic scattering cross section of the singlet fermion into target nuclei for a direct detection of the dark matter. Search of the direct detection of the dark matter provides severe constraints on the parameters of our model.

Keywords: cold dark matter, singlet fermion, singlet scalar

INTRODUCTION

Searches on dark matter have been done since its evidence was first discovered by Zwicky in 1933 \(^2\). The precise measurement of the relic abundance of the cold dark matter (CDM) has been obtained from the Wilkinson microwave anisotropy probe (WMAP) data on the cosmic microwave background radiation as \(^3\)

\[0.085 < \Omega_{CDM} h^2 < 0.119, \quad (2\sigma \text{ level}) \quad (1)\]

where \(\Omega\) is the normalized relic density and the scaled Hubble constant \(h \approx 0.7\) in the units of 100 km/sec/Mpc. Among the Standard Model (SM) contents, there seems to be no appropriate candidate of CDM satisfying this observed constraint on the relic density. Therefore, various candidates of the CDM have been proposed in the models beyond the SM. Among them, WIMP’s are most favored ones because they naturally explain the observed relic density. WIMPs include the lightest supersymmetric particle (LSP) in the supersymmetric models with \(R\) parity \(^4\), the lightest Kaluza-Klein particle in the extra dimensional models with conserved KK parity \(^5\), and the lightest T-odd particle in the T-parity conserved little Higgs model \(^6\). Addition of a real singlet scalar field to the SM with \(Z_2\)-parity has been considered as one of the simplest extensions of the SM with the nonbaryonic CDM \(^8\). On the other hand, a model with a gauge singlet Dirac fermion is proposed as a minimal model of fermionic dark matter \(^11\). In this model, the singlet fermion interacts with the SM sector only through nonrenormalizable interactions among which the leading interaction term is given by the dimension five term \((1/\Lambda) H^\dagger H \bar{\psi} \psi\), where \(H\) is the SM Higgs doublet and \(\psi\) is the dark matter fermion, suppressed by a new physics scale \(\Lambda\).

In this paper, we propose a renormalizable extension of the SM with a hidden sector which consists of SM gauge singlets (a singlet scalar and a singlet Dirac fermion). The singlet scalar interacts with the SM sector through the triple and quartic scalar interactions. There are no renormalizable interaction terms between the singlet fermion and the SM particles but the singlet fermion interacts with the SM matters only via the singlet scalar. Therefore it is natural that the singlet fermion is a WIMP and a candidate of the CDM.

THE MODEL

We introduce a hidden sector consisting of a real scalar field \(S\) and a Dirac fermion field \(\psi\) which are SM gauge singlets. The singlet scalar \(S\) couples to the SM particles only through triple and quartic terms with the SM Higgs boson such as \(SH^\dagger H\) and \(S^2 H^\dagger H\). New fermion number of the singlet fermion is required to be conserved in order to avoid the mixing between the singlet fermion and the SM fermions. The global \(U(1)\) charge of the singlet Dirac fermion takes the role of the new fermion number. As a result, no renormalizable interaction terms between the singlet fermion \(\psi\) and the SM particles are allowed. Thus the interaction of \(\psi\) with the SM particles
just comes via the singlet scalar.

We write the Lagrangian as
\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{\text{hid}} + \mathcal{L}_{\text{int}}, \]
where the hidden sector Lagrangian is given by
\[ \mathcal{L}_{\text{hid}} = \mathcal{L}_S + \mathcal{L}_\Psi - g_S \bar{\psi} \psi S, \]
with
\[ \mathcal{L}_S = \frac{1}{2} \left( \partial_\mu S \right) \left( \partial^\mu S \right) - \frac{m_0^2}{2} S^2 - \frac{\lambda_3}{3!} S^3 - \frac{\lambda_4}{4!} S^4, \]
\[ \mathcal{L}_\Psi = \bar{\psi} \left( i \partial - m_{\psi_0} \right) \psi. \]

The interaction Lagrangian between the hidden sector and the SM fields is given by
\[ \mathcal{L}_{\text{int}} = -\lambda_1 H^\dagger H S - \lambda_2 H^\dagger H S^2. \]

The scalar potential given in Eq. (4) and (5) together with the SM Higgs potential \(-\mu^2 H'^\dagger H + \lambda_0 (H^\dagger H)^2\) derives the vacuum expectation values (VEVs)
\[ \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_0 \end{pmatrix} \]
for the SM Higgs doublet to give rise to the electroweak symmetry breaking, and \(\langle S \rangle = x_0\) for the singlet scalar sector. The neutral scalar states \(h\) and \(s\) defined by \(H^0 = (v_0 + h)/\sqrt{2}\) and \(S = x_0 + s\) are mixed to yield the mass eigenstates \(h_1\) and \(h_2\) such as
\[ h_1 = \sin \theta s + \cos \theta h, \]
\[ h_2 = \cos \theta s - \sin \theta h, \]
with the mixing angle \(\theta\). According to the definition of \(\tan \theta\), we get \(|\cos \theta| > \frac{1}{\sqrt{2}}\) implying that \(h_1\) is SM Higgs-like while \(h_2\) is the singlet-like scalars. As a result, there exist two neutral Higgs bosons in our model and the collider phenomenology of the Higgs sector might be affected.

The singlet fermion \(\psi\) has the mass \(m_\psi = m_{\psi_0} + g_S x_0\) as an independent parameter of the model since \(m_{\psi_0}\) is just a free parameter. The Yukawa coupling \(g_S\) measures the interaction of \(\psi\) with other particles. Generically the interactions between \(\psi\) and the SM particles are suppressed by the mass of singlet scalar and/or the Higgs mixing. Therefore \(\psi\) is naturally weakly interacting and can play the role of a cold dark matter as a WIMP. If we fix masses of two Higgs bosons, the singlet fermion annihilation processes into the SM particles depend upon the fermion mass \(m_\psi\), Yukawa coupling \(g_S\), and the Higgs mixing angle \(\theta\). If the final state includes Higgs bosons, \(h_1\) or \(h_2\), several Higgs self-couplings are involved depending on various couplings in the scalar potential.

**IMPLICATIONS IN COSMOLOGY AND COLLIDER PHYSICS**

Most of our DM fermions are thermally produced so the current relic abundance of the CDM depends on the annihilation cross section of \(\psi\) into the SM particles or the additional Higgs bosons in our model. The pair annihilation process of \(\psi\) consists of the annihilation into SM particles via Higgs-mediated s-channel processes and into Higgs bosons via \(s, t,\) and \(u\)-channels. After the freeze out of the annihilation processes, the actual number of \(\psi\) per comoving volume becomes constant and the present relic density \(\rho_\psi = m_\psi n_\psi\) is determined. The freeze-out condition gives the thermal relic density in terms of the thermal average of the annihilation cross section.

\[ \Omega_\psi h^2 \approx \frac{(1.07 \times 10^9) x_F}{\sqrt{g} M_{pl}(\text{GeV}) \langle \sigma_{\text{ann}, \text{rel}} \rangle}, \]

where \(g\), counts the effective degrees of freedom of the relativistic quantities in equilibrium and \(x_F = m_\psi/T_F\) is the inverse freeze-out temperature for the freeze-out temperature \(T_F\).

We investigate the allowed model parameter space, which provides thermal relic density consistent with the WMAP observation. For clarity of the presentation of our result, we fix the Higgs masses, \(m_{h_1}\) and \(m_{h_2}\) within some ranges, while allowing the other parameters such as Higgs mixing angle and self couplings vary freely. Our parameter sets should satisfy several physical conditions. We demand that \(i\) the potential is bounded from below, \(ii\) the electroweak symmetry breaking is viable, and \(iii\) all couplings keep the perturbativity. Among all the figures we have scanned, we show the most interesting one here. Fig. 1 shows the allowed parameter set

**FIGURE 1.** Allowed parameter set \((m_\psi, g_s)\) on the domain \(\{20 \text{GeV} \leq m_\psi \leq 100 \text{GeV}, 10^{-3} \leq g_s \leq 10\}\), \(m_{h_1} = 120 \text{GeV} (\pm 4\%); m_{h_2} = 100 \text{GeV} (\pm 1\%); 0.00150509 \leq \theta \leq 735986 \text{ in radian}; m_t = 174.3 \text{GeV}; m_b = 4.8 \text{GeV}; m_W = 79.9341 \text{GeV}; m_Z = 91.2 \text{GeV}; T = m_\psi/20\)

for \(m_{h_1} = 120 \text{GeV} \) and \(m_{h_2} = 100 \text{GeV} \). Here \(m_{h_1}\) and \(m_{h_2}\) are comparable and there are two resonant regions corresponding to \(h_1\) and \(h_2\) resonances. The current experimental bound on Higgs mass can have a significant
impact on the allowed parameter space. Because of the presence of the two higgs bosons mixed with the singlet sector, it is allowed to have higgs mass lower than the typical bound 114.4 GeV by LEP2. The promising channel to produce a neutral Higgs boson at LEP is the Higgs-strahlung process, $e^-e^+ \rightarrow Zh$. The altered higgs couplings in our model provide appropriate mass bounds on our higgs according to [12], and Fig.1 shows one of the most promising parameter space where most of the region are allowed even by LEP2 experiments.

**DIRECT DETECTION**

There are several experiments to detect the WIMP directly through the elastic scattering of the WIMP on the target nuclei [13, 14]. In our model, the singlet fermionic dark matter interacts with the target nuclei through $t$-channel process. The prediction of the elastic scattering cross sections is depicted in Fig.2. Allowed parameter region by the masses and couplings at LEP2 are included and the elastic scattering cross sections for the direct detection are predicted. We find that most region of the parameter set will be probed by the direct detection through elastic scatterings of the DM with nuclei in the near future.

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