Can A Higgs Portal Dark Matter be Compatible with the Anti-proton Cosmic-ray?

Hiroshi Okada\textsuperscript{a} and Takashi Toma\textsuperscript{b,c}

\textsuperscript{a}School of Physics, KIAS, Seoul 130-722, Korea
\textsuperscript{b}Institute for Theoretical Physics, Kanazawa University, Kanazawa, 920-1192, Japan
\textsuperscript{c}Max-Planck-Institut f"ur Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Abstract

Recent direct detection experiments of Dark Matter (DM), CoGeNT and DAMA implicate a light DM of a few GeV. Such a light DM would generate a large amount of anti-proton since suppression for anti-proton flux from DM annihilation is ineffective. We discuss whether a light dark matter with mass of $5 - 15$ GeV, which is especially in favor of the recent experiments reported by CoGeNT, is compatible with the anti-proton no excess in the cosmic-ray. In view of the direct detection of DM and no anti-proton excess in the cosmic-ray both, we show that a Dirac DM is favored than a scalar one since there is no s-wave of the annihilation cross section for the Dirac DM. A large elastic cross section for direct detection can be obtained through the additional light Higgs exchange. We show an allowed region that simultaneously satisfies the DM relic density, the elastic cross section favored by CoGeNT and also the constraint of $H_LZZ$ coupling of the light Higgs boson by LEP.
1 Introduction

The existence of Dark Matter (DM) is crucial from cosmological observations such as the rotation curves of the galaxy \cite{1}, the CMB observation by WMAP \cite{2}, gravitational lensing \cite{3}. However, since DM candidate particle is not included in the Standard Model (SM), the SM should be extended to include DM candidate. In recent years, direct detection experiments of DM such as XENON100 \cite{4}, CDMSII \cite{5}, CRESSTII \cite{6}, CoGeNT \cite{7} and DAMA \cite{8} are extremely active to look for scattering events with nuclei. While XENON100 and CDMSII have shown null result of DM signal, CoGeNT, DAMA and CRESSTII have reported the observations which can be interpreted as DM signals. The discrepancy among these experiments could be improved by considering a non-standard DM scattering model like inelastic scattering \cite{9,10}, or a non-spherical DM profile like tri-axiality \cite{11,12}. The CoGeNT and DAMA results observing annual modulation of DM signals favor a light DM with several GeV mass and rather large scattering cross section with nuclei. If the CoGeNT and DAMA results are truly DM signals, we need a DM model which is consistent with the other constraints such as the DM thermal relic density, the observation of anti-proton cosmic-ray. In case of taking into account a light DM, anti-proton emission in the cosmic-ray due to annihilation of DM would increase. This is because the source term of the anti-proton flux from DM annihilation is

$$\langle \sigma v_{\text{rel}} \rangle \rho_{\odot}^2 / 2m_{DM}^2,$$

where $\langle \sigma v_{\text{rel}} \rangle$ is annihilation cross section of DM, $\rho_{\odot} \simeq 0.3$ GeV/cm$^3$ is the local DM density at the Earth and $m_{DM}$ is DM mass. Thus we can see that suppression of the source term by DM mass does not work efficiently for 10 GeV scale DM.

The minimal extension of the SM which includes DM candidate is the model with Higgs portal gauge singlet real scalar $S$ \cite{13}. This model is fascinating since the annihilation cross section required to make the correct DM relic density and the elastic cross section with nuclei favored by CoGeNT and DAMA are simultaneously obtained at roughly 10 GeV DM mass. However if the constraint from the anti-proton cosmic-ray should be taken into account, this model is severely restricted \cite{14,15,16}. In order to escape the anti-proton constraint, the annihilation cross section of DM should be p-wave dominant. If so, the annihilation cross section is extremely suppressed by the relative velocity $v_{\text{rel}} \sim 10^{-3}$ at the present Universe. In this paper, we discuss a next minimal DM model which has a gauge singlet real scalar $S$ and a Dirac fermion $\Psi$, and the Dirac fermion is identified to be DM candidate with p-wave dominant annihilation cross section\cite{1}. In this scenario, the singlet real scalar $S$ is assigned as even charge under the $\mathbb{Z}_2$ parity which is different from the minimal DM model. Thus the SM model Higgs $h$ and the singlet real scalar $S$ mix and the mixing is limited by the

\footnotetext{1}{Other scenarios are considered overcome it. See, e.g., Ref. \cite{17,18,19}.
The elastic scattering of DM with nuclei for direct detection occurs through the Higgs exchange, hence the contribution through the light Higgs becomes larger than that through the heavy Higgs. As a result, a large elastic cross section of DM required from CoGeNT is expected to be obtained. We investigate whether the DM relic density and the rather large elastic cross section favored by CoGeNT are satisfied simultaneously in the allowed parameter space from the Higgs mixing bound by LEP.

This paper is organized as follows. In Section 2, we review the minimal Higgs portal DM model and discuss the next minimal DM model with a Dirac fermion. In Section 3, direct detection of DM in the next minimal DM model is discussed. We summarize and conclude in Section 4.

2 The Model

2.1 The Minimal Model

At first we start to discuss a gauge singlet real scalar DM ($S$) in the simplest model. The Lagrangian is typically given as

\[ \mathcal{L} = y_u \bar{Q} H U_R + y_d \bar{Q} H D_R + y_l \bar{L} H E_R + h.c. \]

\[ - \frac{m_S^2}{2} S^2 - m_H^2 H^\dagger H - \frac{\lambda_H}{2} (H^\dagger H)^2 - \frac{\lambda_S}{4} S^4 - \frac{\lambda_{SH}}{2} S^2 (H^\dagger H), \]

(2.1)

where the odd $\mathbb{Z}_2$ parity is imposed to $S$ to guarantee the DM stability and the family index is omitted. Here $H$ is SM Higgs and $\tilde{H} \equiv i \sigma_2 H^*$. Note that $S$ is the mass eigenstate at this Lagrangian since it does not mix with SM Higgs because of the $\mathbb{Z}_2$ parity. After the spontaneous symmetry breaking; $H = (0, v + h/\sqrt{2})^t$ with $v=174$ GeV, one finds the interacting terms between Higgs and matter fields as

\[ \mathcal{L} \supset \frac{y_u}{\sqrt{2}} \bar{U}_L U_R h + \frac{y_d}{\sqrt{2}} \bar{D}_L D_R h + \frac{y_l}{\sqrt{2}} \bar{E}_L E_R h - \frac{\lambda_{SH}}{2} S^2 h + h.c. \]

(2.2)

The singlet scalar $S$ annihilates to the SM fermions $j \bar{j}$ through the neutral Higgs boson exchange. Here notice that the dominant contribution comes from bottom pair final state as one can see from the hierarchy of the Yukawa coupling, thus we consider the $b \bar{b}$ process only hereafter. The annihilation cross section of the singlet scalar is calculated as

\[ \sigma v_{rel} \simeq \frac{3 \lambda_{SH}^2 v^2}{16\pi} \left( \frac{1}{s - m_h^2} \right)^2 \bar{y}_b^2 \left( 1 - \frac{m_b^2}{m_{DM}^2} \right) \left[ 1 - \frac{m_b^2}{m_{DM}^2} \right] + \mathcal{O}(v_{rel}^4), \]

(2.3)
Figure 1: The left figure is s-wave and p-wave contribution of the annihilation cross section Eq. (2.3) in the early Universe epoch. The horizontal black line is the annihilation cross section; $\sigma_{v_{\text{rel}}} = 3 \times 10^{-9}$ GeV$^{-2}$, satisfying the DM relic density $\Omega h^2 = 0.11$ from the WMAP [2]. The right figure is the s-wave contribution and the allowed parameter region from the anti-proton no excess in the cosmic-ray observations. Notice that the p-wave contribution is negligible compared with the s-wave one. The blue region is allowed from the anti-proton constraint in the case of the NFW DM profile [21].

where $m_{DM}^2 = m_S^2 + \lambda_{SH} v^2$ and $v_{\text{rel}}$ is the relative velocity of the annihilating DM.

The left panel of Fig. 1 shows s-wave and p-wave contribution of Eq. (2.3) at the early Universe ($v_{\text{rel}} \sim 0.3$) where we take $m_b = 4.67$ GeV [22], $\lambda_{SH} \leq 1$ and $m_h = 125$ GeV [23]. The horizontal black line implies the annihilation cross section required to get the correct DM relic density from WMAP, which is roughly $\sigma_{v_{\text{rel}}} \sim 3 \times 10^{-9}$ GeV$^{-2}$. In the right panel of Fig. 1 the s-wave contribution at the present Universe and allowed parameter region from the anti-proton no excess in the cosmic-ray observations [24, 25, 26, 27, 28] are shown. The p-wave contribution can be neglected due to $v_{\text{rel}} \sim 10^{-3}$ at the time. As shown in the figure, the s-wave contribution should be less than $O(10^{-10})$ GeV$^{-2}$ to satisfy the anti-proton no excess if a few GeV DM is taken into account. From these figures, we can see that the annihilation cross section in the minimal singlet scalar model cannot satisfy both of the relic density required by WMAP and the anti-proton no excess in the cosmic-ray at the present Universe. It suggests that the annihilation cross section required by WMAP should be generated by p-wave contribution. Hence we conclude that the minimal model cannot be consistent with the
DM relic density of the light DM and no anti-proton excess in the cosmic-ray. Note that there is an ambiguity for the anti-proton constraint which depends on DM profiles such as NFW, Einasto and Burkert and on propagation models of cosmic-ray. In particular the dependence on the vertical scale of the diffusion zone is significant. If we choose an only small value of the parameter, it is possible to keep consistency with the constraint. This is discussed in [14] in detail.

The minimal model also strongly affects the SM Higgs invisible decay [29, 30, 31, 32]. The large $hSS$ coupling gives an impact to the branching ratio of the Higgs invisible decay and can be dominant Higgs decay channel when the mass of the singlet scalar $S$ is less than 40 GeV [29]. It makes difficult to search an evidence of DM in the minimal model by collider experiments.

2.2 The Next Minimal Model

In order to solve the problem of the anti-proton cosmic-ray, we propose a next minimal model, in which only the difference is that a Dirac fermion $\Psi$ is newly added to the minimal singlet scalar model where the $\mathbb{Z}_2$ parity is imposed to odd for the $\Psi$ and even for the other particles including the singlet scalar $S$. Thus the Dirac fermion $\Psi$ can be a DM candidate in this model. It is worth mentioning that in the same model S. Baek, P. Ko, and Wan-Il Park group have recently discussed to analyze the other aspects such as perturbative unitarity, electroweak precision test and LHC detectability with direct DM search at $\mathcal{O}(100)$ GeV, in which they have shown an good agreement with those experiments [33]. The singlet scalar $S$ cannot be a DM in the next minimal model due to the even assignment of the $\mathbb{Z}_2$ parity. The additive Lagrangian to the SM is written as

$$
\mathcal{L} = g S \overline{\Psi} \Psi - m_{DM} \overline{\Psi} \Psi - m_{H}^2 H\dagger H - \frac{m_{S}^2}{2} S^2 - \lambda_H \left( H\dagger H \right)^2 \\
- \mu_S S (H\dagger H) - \frac{\lambda_{SH}}{2} S^2 \left( H\dagger H \right) - \mu_1 S - \frac{\mu_2}{3} S^3 - \frac{\lambda_S}{4} S^4.
$$

Here notice that Higgs sector is no longer the mass eigenstate because Higgs mixing term appears from the interaction $SH\dagger H$. Assuming all the parameters in the Higgs sector are real, that is, there is no CP violation, we find the Higgs mass matrix in the basis of $(h, S)^t$. It can be diagonalized by

\[ \text{Although in general the pseudo scalar coupling such as } S \overline{\Psi} \gamma_5 \Psi \text{ also exists, here we do not consider it since the pseudo scalar coupling generates s-wave to the DM annihilation cross section.} \]
the following mixing matrix as
\[
\mathbf{M}_{\text{Higgs}}^2 \equiv \begin{pmatrix}
4\lambda_H v^2 & 2\sqrt{2}\mu_S v \\
2\sqrt{2}\mu_S v & m_S^2 + 2\lambda_S h v^2
\end{pmatrix}
\]
\[
= \begin{pmatrix}
\cos \alpha & \sin \alpha \\
-\sin \alpha & \cos \alpha
\end{pmatrix}
\begin{pmatrix}
m_{H_L}^2 & 0 \\
0 & m_{H_H}^2
\end{pmatrix}
\begin{pmatrix}
\cos \alpha & -\sin \alpha \\
\sin \alpha & \cos \alpha
\end{pmatrix},
\]
(2.5)
where we inserted the stable condition: \( m_H^2 = -2\lambda_H v^2 \), \( \mu_1^2 = -\mu_S v^2 \) and we assumed that \( S \) has no vacuum expectation value. The gauge eigenstates \( h \) and \( S \) can be rewritten in terms of the mass eigenstates of \( H_L \) and \( H_H \) as
\[
h = H_L \cos \alpha + H_H \sin \alpha,
\]
\[
S = - H_L \sin \alpha + H_H \cos \alpha.
\]
(2.6)
Then the Lagrangian includes the interactions with the light Higgs boson \( H_L \)
\[
\mathcal{L} = - g \sin \alpha \overline{\Psi} \Psi H_L + \frac{y_b \cos \alpha}{\sqrt{2}} b_L b_R H_L + \text{h.c.},
\]
(2.7)
where we omit the heavy Higgs contribution. From the interactions, the annihilation cross section for \( \overline{\Psi} \Psi \to ff \) through the light scalar boson \( H_L \) can be written as
\[
\sigma v_{\text{rel}} \simeq \frac{3g^2 y_b^2 m_{DM}^2}{16\pi} \frac{\sin^2 \alpha \cos^2 \alpha}{(s - m_{H_L}^2)^2 + m_{H_L}^2 \Gamma_{H_L}^2} \left( 1 - \frac{m_b^2}{m_{DM}^2} \right)^{3/2} v_{\text{rel}}^2 + \mathcal{O}(v_{\text{rel}}^4),
\]
(2.8)
where \( \Gamma_{H_L} \) is the total decay width of the light Higgs \( H_L \). When \( 2m_b < m_{H_L} < 2m_{DM} \), the decay width is
\[
\Gamma_{H_L} \simeq \frac{y_b^2 \cos^2 \alpha}{8\pi} m_{H_L} \left( 1 - \frac{4m_b^2}{m_{DM}^2} \right)^{3/2},
\]
(2.9)
and when \( 2m_{DM} < m_{H_L} \), the channel \( H_L \to \text{DM DM} \) is also added. we neglected the light quarks contributions and put only bottom quark contribution. If DM is heavier than the light Higgs \( H_L \), the annihilation channel DM DM \( \to H_L H_L \) is also possible and it is large enough to obtain proper relic abundance of DM. However as we will see Fig. 4 in Section 3 since the light Higgs mass should be heavier than DM in order to fit the CoGeNT result, we do not take into account the channel here. The annihilation to \( b\overline{b} \) is dominant as same as the minimal singlet scalar model. We can obtain no s-wave in the annihilation cross section, thus the anti-proton constraint from the cosmic-ray at the present Universe is consistent as we discussed before.

The Higgs mixing \( \sin \alpha \) is strongly constrained by the \( H_L ZZ \) coupling measurement. The LEP data are used to set upper bound on the \( H_L ZZ \) coupling [20]. The excluded region of \( \sin^2 \alpha \) by LEP
Figure 2: LEP bound of the light neutral Higgs boson $H_L$. The red region is excluded by the LEP data. The light Higgs mass should be $m_{H_L} \lesssim 50$ GeV to be consistent with the required annihilation cross section by WMAP and the elastic cross section favored from CoGeNT as discussed later. Thus the mass range of Fig. 2 is enough in the discussion. We can see from the Fig. 2 that region of $\sin \alpha \simeq 1$ is only allowed from the LEP bound in this mass region. This implies that the off-diagonal element of the Higgs mass matrix Eq. (2.5) must be small, namely small $\mu_S$.

The light Higgs $H_L$ might affect to the decay of the heavy Higgs boson which corresponds to the SM Higgs boson. The new invisible decay channel $H_H \to H_L H_L$ appears and the branching ratio of the channel is proportional to the coupling $\lambda_{SH} \sin^3 \alpha$. If the branching fraction of the invisible decay $H_H \to H_L H_L$ is too large, the next minimal model is ruled out by the recent LHC result as analyzed in the other models \cite{34}. However fortunately, we can take a small value of the coupling since the coupling $\lambda_{SH}$ is not relative with DM physics which is different from the minimal model.

The cusp profile such as NFW is favored from the N-body simulations of collisionless DM. On the other hand, the X-ray observations of clusters suggest that DM density profile is approximately flat. The discrepancy between the simulations and the observations of the galaxies might be alleviated by taking into account the self-interaction of DM \cite{35, 36, 37, 38}. The elastic cross section of DM must satisfy $\sigma/m_{DM} \lesssim 1$ cm$^2$/g to be consistent with the observations. The constraint becomes important in the case of considering MeV scale DM or some enhancement mechanism of elastic (annihilation)
cross section of DM like Sommerfeld enhancement \cite{39}. In the model, t-channel through the light Higgs $H_L$ is dominant for the elastic cross section of DM, and it is rather enhanced by intermediating the light Higgs. However, the enhancement is not so large and we do not need to take into account the constraint from the self-interaction of DM.

### 3 Direct Detection

We analyze the direct detection search of DM through CoGeNT \cite{7}. The global fit analysis in DM mass and elastic cross section plane has been performed in Ref. \cite{40}. In this model the main contribution to the spin-independent (SI) cross section comes from the t-channel diagram intermediated by the light Higgs $H_L$ as depicted in Fig. 3. Then the resultant SI elastic cross section with nucleon is given by

\[
\sigma_{SI}^N \simeq \frac{\mu_{DM}^2}{\pi} \left( \frac{g m_N \sin \alpha \cos \alpha}{m_{H_L}^2 v} \sum_q f_q^N \right)^2,
\]

where $\mu_{DM} = (m_{DM}^{-1} + m_N^{-1})^{-1}$ is the DM-nucleon reduced mass and the heavy Higgs contribution is neglected. We can see from the Eq. (3.1) that the elastic cross section vanishes if $\sin \alpha$ approaches to 1 because of $\cos \alpha \to 0$. This behavior is same as that for the annihilation cross section Eq. (2.8). We can obtain a large SI elastic cross section due to the propagation of the light Higgs. The parameter $f_q^N$ stands for the contribution of each quark to nucleon mass and these are calculated from the lattice simulation \cite{41, 42} as

\begin{align*}
    f_u^p &= 0.023, \quad f_d^p = 0.032, \quad f_s^p = 0.020, \\
    f_u^n &= 0.017, \quad f_d^n = 0.041, \quad f_s^n = 0.020,
\end{align*}

for the light quarks. For the heavy quarks, the parameters are given as $f_Q^N = 2 \left( 1 - \sum_{q \leq 3} f_q^N \right) / 27$ where $Q$ stands for the heavy quarks and $q \leq 3$ implies the summation of the light quarks.

The contours of the SI elastic cross section $\sigma_{SI}^p$ with proton for $\sin \alpha = 0.980, 0.985, 0.990$ and $g = 0.5, 1.0, 1.5$ are shown in Fig. 4 in the $m_{DM} - m_{H_L}$ plane. The green and red colored regions are 90\% and 99\% confidence levels (CL) for CoGeNT. The yellow lines show that the annihilation cross section of DM is $\sigma v_{rel} \simeq 3.0 \times 10^{-9}$ GeV$^{-2}$ required to satisfy the correct DM relic density. The dark colored regions are excluded by the Higgs mixing bound from LEP experiment. There is no LEP constraint for $\sin \alpha = 0.990$ as seen from Fig. 2. From the figures, we can see that the DM relic density lines and 90\% CL region of CoGeNT are consistent when $\sin \alpha$ and $g$ are $0.980 - 0.990$ and $1.0 - 1.5$. In the case of $g = 0.5$, we need a narrow resonance point in order to satisfy the DM...
Figure 3: The t-channel diagram for the direct detection of DM.

relic density since Yukawa coupling is too small. Instead of that, too small elastic cross section is obtained in that case. Therefore rather large Yukawa coupling $g$ is required to be consistent with these two aspects of DM in the allowed Higgs mixing region by LEP.

4 Conclusions

The Higgs portal DM model which includes a singlet real scalar DM $S$ is the minimal extension of the SM. If a few GeV DM is taken into account as CoGeNT and DAMA suggest it, the DM in the model can be consistent with the DM relic density and the rather large elastic cross section favored by CoGeNT. However, no excess of the anti-proton in the cosmic-ray emerges in this case since the suppression by DM mass for the source term of the anti-proton flux from the DM annihilation is no longer effective, and the annihilation cross section includes the dominant s-wave.

To improve it we have considered that a next minimal DM model which includes a new Dirac fermion into the Higgs portal minimal DM model and have reassigned the $\mathbb{Z}_2$ parity so that the Dirac fermion can be DM candidate. We found that the fermionic DM is promising in the simplest model as a result of analyzing the anti-proton no excess and the relic density. Since the DM has no s-wave in the annihilation cross section and has only p-wave, the source term of anti-proton flux from the DM annihilation was strongly suppressed at the present Universe.

On the other hand, the SM Higgs $h$ and singlet scalar $S$ mix after the electroweak symmetry breaking in the next minimal model. Thus the $H_LZZ$ coupling for the light eigenstate of Higgs is severely constrained by the LEP data. The allowed parameter space of the mixing angle implies small interaction of Higgs $\mu_S S(H^1H)$. In numerical analyses, we have found that the DM relic density lines and 90% CL parameter region of CoGeNT can be consistent when the Higgs mixing angle $\sin \alpha$ and the Yukawa coupling $g$ are $0.980 - 0.990$ and $1.0 - 1.5$ respectively. Thus rather large Yukawa coupling
Figure 4: The yellow lines imply that the correct DM relic density is obtained. The red and green regions show the favored parameter space by CoGeNT. The blue, violet and light blue lines are contours of the SI elastic cross section.

$g$ is favored. Although only narrow Higgs mixing angle is allowed from the LEP data, the DM relic density and the CoGeNT favored SI elastic cross section can be consistent in the next minimal Dirac DM model.
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