\( \nu_R \) dark matter-philic Higgs for 3.5 keV X-ray signal

Naoyuki Haba, Hiroyuki Ishida and Ryo Takahashi

Graduate School of Science and Engineering, Shimane University, Matsue, 690-8504 Japan

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Abstract

We suggest a new model in which a dark matter-philic Higgs is included to discriminate the interaction between dark matter and other particles, to explain the recent observation of the 7 keV X-ray line signal by XMM-Newton observatory. The smallness of the vacuum expectation value of dark matter-philic Higgs can achieve the small mixing angle of the dark matter right-handed neutrino with the ordinary one. We show the range of the symmetry breaking scales as well as the observed dark matter properties are satisfied. In our model, the value of the vacuum expectation value of dark matter-philic Higgs should be about 0.17 GeV.
# 1 Introduction

The existence of dark matter (DM) is certainly confirmed by a lot of astrophysical observations. If it, however, is consisted by an elementary particle, there is no candidate in the standard model (SM) particle content which is finalized by the observation of the Higgs particle. For extensions of the SM to include its candidate, we have to make a lifetime of DM candidate particle to be longer than the age of the universe. To ensure it, an additional symmetry may become a plausible possibility. For instance, when we assign odd parity to DM particle and even parity to all others under a $Z_2$ symmetry, it can be completely stable particle in whole age of the universe. In this way, additional symmetries can become a key ingredient for the sufficient long lifetime particles.

Recent analyses of the observation of X-ray from the Perseus galaxy clusters and the Andromeda galaxy by XMM-Newton reported an unknown X-ray line spectrum around 3.5 keV [1, 2]. The origin of this line cannot be explained by astrophysical phenomena so far. Therefore, we try to understand by particle physical explanations and consider that it comes from a decay of a light DM particle. So many articles [3]-[30] in which DM can decay into a photon through some mechanisms are appeared after these announcements. One attractive solution is right-handed neutrino, $\nu_R$, with its mass around 7 keV [31]. In this scenario, the experiments constrain the squared mixing angle between left- and right-handed neutrinos denoted by $\Theta$ as $\Theta^2 = (0.55 - 5.0) \times 10^{-11}$.

On the other hand, right-handed neutrinos are well known for providing tiny neutrino masses through the seesaw mechanism [32]. In general, the Lagrangian for the neutrino sector in the seesaw mechanism can be described as

$$L_{\text{seesaw}} = -y_{\alpha I} \bar{L}_\alpha \tilde{H} \nu_{RI} + \frac{M_N}{2} \bar{\nu}_{RI} \nu_{RI},$$

where $\tilde{H} = i \sigma_2 H^*$, and $L$ and $H$ are lepton and Higgs doublets, $M_N = \text{diag}(M_1, M_2, M_3)$ is Majorana mass, and $\alpha = e, \mu, \tau$ and $I = 1 - 3$ represent the flavor of left-handed lepton and right-handed neutrinos. Regarding the right-handed neutrino mass spectrum, hierarchical mass spectrum can solve several issues such as the tiny neutrino masses, DM candidate, and baryon asymmetry of the universe at the same time (e.g. see [33, 34, 35, 36]). Such a hierarchical structure among Majorana masses can be realized by e.g., the Froggatt-Nielsen mechanism [37, 38], the split seesaw mechanism [34], the lepton flavor symmetry [39], and so on. After breaking the electroweak symmetry, we have two types of the mass terms of neutrinos; Dirac mass term, $(M_D)_{\alpha I} = y_{\alpha I} v$ with $v \equiv \langle H \rangle$, and Majorana mass term. Thus, the seesaw mechanism explain the tiny neutrino masses as $m_\nu = -M_D^2/M_N$ with $m_\nu \sim \mathcal{O}(0.1) \text{ eV}$ under an assumption of $M_D \ll M_N$ even though we suppose such hierarchical mass spectrum in the Majorana masses. The mixing angle between left- and right-handed neutrinos is given by these two masses as $\Theta_{\alpha I} = (M_D)_{\alpha I}/M_I$. When we assume the lightest Majorana mass is of the order keV and

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#1See [31] for a review of keV dark matter model building.
seesaw relation, the squared mixing angle of $\nu_{R1}$ can be estimated as

$$\Theta^2 = \sum_{\alpha} \Theta_{\alpha 1}^2 \simeq \left( \frac{M_D}{M_1} \right)^2 = \frac{m_{\nu}}{M_1} \sim 10^{-4} \gg 10^{-11}. \quad (2)$$

Note that the observed magnitude of the mixing angle never achieve unless giving up the seesaw relation. One way to realize an acceptable size of left-right mixing angle is to take small neutrino Yukawa couplings only for the first generation of the right-handed neutrinos such that the mass scale of $(y_{\alpha 1} v)^2/M_1$ is much smaller than the atmospheric neutrino mass scale, $(y_{\alpha 1} v)^2/M_1 \ll m_{\nu} \sim \mathcal{O}(0.1)$ eV.

In this work, we suggest another possibility to realize a suitable left-right mixing due to the deviation from the seesaw relation by a simple extension of the SM. To do that, we consider an extended model with a DM-philic Higgs field, $H_{DM}$, which constitutes a Yukawa interaction of DM with ordinary SM fields.

2 DM-philic Higgs model

2.1 Basic idea

The results from X-ray observation experiments indicate the existence of an unknown particle which has a mass around 7 keV. If we assume it is right-handed neutrino, it should not contribute to the active neutrino mass scale through the seesaw relation due to its small mass and mixing angle between ordinary neutrinos as already discussed. Such property indicates the right-handed neutrino DM (RH$\nu$DM) has a different interaction with the ordinary matters. We consider an extended model including RH$\nu$DM-philic Higgs, $H_{DM}$, which can distinguish the coupling among the RH$\nu$s.

By introducing this additional Higgs, the relevant Lagrangian is given by

$$L'_{\text{seesaw}} = -y_{\alpha 1} \bar{L}_\alpha H_{DM} \nu_{R1} - y_{\alpha i} \bar{L}_\alpha \tilde{H} \nu_{Ri} + \frac{M_N}{2} \tilde{\psi}_{R1}^c \psi_{R1}, \quad (3)$$

where $i = 2, 3$ and we suppose that $M_1 \ll M_{2,3}$ at this moment. Therefore, we can realize a small mixing of $\nu_{R1}$ by taking small vacuum expectation value (VEV) of $H_{DM}$, $v_{DM}$. With this very simple setup, the mixing angle can be represented as

$$\Theta^2 \simeq \left( \frac{y_{\alpha 1} v_{DM}}{M_1} \right)^2 = \left( \frac{v_{DM}}{v} \right)^2 \left( \frac{y_{\alpha 1} v}{M_1} \right)^2 = \left( \frac{v_{DM}}{v} \right)^2 \frac{m_{\nu}}{M_1} \sim \left( \frac{v_{DM}}{v} \right)^2 \times 10^{-4}, \quad (4)$$

where $v_{DM}$ is the VEV of another Higgs $H_{DM}$ and the third and fourth equalities are given by Eq. (2). One can see that when $(v_{DM}/v)^2 = \mathcal{O}(10^{-7})$, that is $v_{DM}$ is the order of 0.1 GeV, the observed X-ray flux can be explained. Instinctively, the deviation from seesaw formula is realized the small value of $v_{DM}$ rather than fine-tuning of coupling constants. This is our main idea and this possibility is really simple.

#2For other possibilities, the extra-dimensional extension and the extended B-L structure are considered.
Table 1: The charge assignments for each field. $n$ is an arbitrary natural number.

|       | $H$ | $\tilde{H}_{\text{DM}}$ | $\Phi_{\text{FN}}$ | $\Phi_{\text{B-L}}$ | $\nu_{R1}$ | $\nu_{Ri}$ |
|-------|-----|------------------------|--------------------|---------------------|------------|-----------|
| $U(1)_{\text{B-L}}$ | 0   | 0                      | 0                  | 2                   | -1         | -1        |
| $U(1)_{\text{FN}}$  | 0   | 0                      | -1                 | 0                   | $n$        | 0         |
| $Z_2$   | +   | -                      | +                  | +                   | -          | +         |

2.2 Simple model

Next, we show an example of models. The charge assignments for each field are summarize in the Tab. 1. We also extend the symmetry by imposing gauged $U(1)_{\text{B-L}}$ which is responsible not only for the generation of the Majorana masses of RH$\nu$s but also DM production, and two global symmetries $U(1)_{\text{FN}}$ and $Z_2$ which provide the sufficient hierarchy of the mass and the coupling between $\nu_{R1}$ and others. $U(1)_{\text{B-L}}$ and $U(1)_{\text{FN}}$ are spontaneously broken by a $B-L$ Higgs boson, $\Phi_{\text{B-L}}$ and another Higgs, $\Phi_{\text{FN}}$, respectively. Those breaking scales are denoted as $v_{B-L}$ and $v_{FN}$, respectively.

The relevant Lagrangian under these symmetries are written down as

$$L = L_{\text{SM}} + L_\nu, \quad (5)$$

$$L_\nu = y_{ai} \tilde{L}_a \tilde{H} \nu_{Ri} + \lambda_{ij} \Phi_{\text{B-L}} \tilde{\nu}_{Ri} \nu_{Rj} + \frac{\lambda_{11}}{\Lambda^2} \Phi_{\text{FN}} \Phi_{\text{B-L}} \tilde{\nu}_{R1} \nu_{R1}, \quad (6)$$

where $L_{\text{SM}}$ contains the terms under the SM gauge symmetries, $y$ and $\lambda$ are the dimension-less coupling constants, and $\Lambda$ represents the cutoff scale.

Next, we move the story onto the Higgs potential. In order to make a success with this model, the small value of $v_{\text{DM}}$ is essential. We show the validity of this point below. The corresponding Higgs potential of this model is

$$V = m_1^2 |H|^2 + m_2^2 |H_{\text{DM}}|^2 - m_3^2 (H^\dagger H_{\text{DM}} + H_{\text{DM}}^\dagger H) + \frac{\lambda_1}{2} |H|^4 + \frac{\lambda_2}{2} |H_{\text{DM}}|^4$$

$$+ \lambda_3 |H_{\text{DM}}|^2 |H|^2 + \lambda_4 |H^\dagger H_{\text{DM}}|^2 + \frac{\lambda_5}{2} \left[ (H^\dagger H_{\text{DM}})^2 + (H_{\text{DM}}^\dagger H)^2 \right], \quad (7)$$

where $m_3^2 (H^\dagger H_{\text{DM}} + H_{\text{DM}}^\dagger H)$ terms, which softly break $Z_2$ symmetry. Thus, the lightest RH$\nu$ can be a decaying DM. A stationary condition $\partial V/\partial v_{\text{DM}} = 0$ gives

$$v_{\text{DM}} \simeq \frac{m_2^2 v}{m_2}, \quad (8)$$

where we assume $\sqrt{\lambda_3} v, \sqrt{\lambda_4} v \ll m_2$. Note that when one takes $m_3 \ll m_2$ in Eq. (8), a tiny value of $v_{\text{DM}}$ can be realized.
After obtaining the VEV of each scalar field, the Dirac and Majorana mass matrix can be written as

\[
M_D = \begin{pmatrix}
\lambda_{11} v_{FN}^n v_{DM} & y_{12} v & y_{13} v \\
\lambda_{21} v_{FN}^n v_{DM} & y_{22} v & y_{23} v \\
\lambda_{31} v_{FN}^n v_{DM} & y_{32} v & y_{33} v
\end{pmatrix},
\]

(9)

\[
M_M = \begin{pmatrix}
\lambda_{11} \Lambda v & 0 & 0 \\
\lambda_{22} \Lambda v & \lambda_{23} \Lambda v_{B-L} \\
\lambda_{32} \Lambda v & \lambda_{33} \Lambda v_{B-L}
\end{pmatrix}.
\]

(10)

The hierarchical structure of the Majorana masses like \(M_1 \ll M_{2,3}\) and the different coupling property in the Dirac mass term are realized.

The seesaw mechanism provides the mass matrix for the lighter mass eigenstate of neutrinos, \(M_\nu\) as

\[
(M_\nu)_{\alpha\beta} = \lambda_{\alpha1} \lambda_{\beta1} \frac{v_{FN}^n v_{DM}^2}{\Lambda^{2n} M_1} + \sum_i y_{\alpha i} y_{\beta i} \frac{v^2}{M_i},
\]

(11)

where \(M_i (i = 2, 3)\) are obtained by the diagonalization of Eq. (10). This mass matrix can be diagonalized by so-called the MNS matrix, \(U\), as \(M_\nu^{\text{diag}} = \text{diag}(m_1, m_2, m_3) = U^\dagger M_\nu U^*\). Roughly speaking, the order of \(m_I\) can be estimated in the normal mass ordering case as

\[
m_1 \simeq \lambda_{\alpha1} \lambda_{\beta1} \frac{v_{FN}^n v_{DM}^2}{\Lambda^{2n} M_1} \simeq \frac{\lambda_{\alpha1} \lambda_{\beta1}}{\lambda_{11}^{2n}} \frac{v_{DM}^2}{v_{B-L}^2},
\]

(12)

\[
m_i \simeq y_{\alpha i} y_{\beta i} \frac{v^2}{M_i} = \frac{y_{\alpha i} y_{\beta i}}{\lambda_{ij}} \frac{v^2}{v_{B-L}^2},
\]

(13)

where \(m_3\) is of the order of \(m_\nu \sim \mathcal{O}(0.1)\) eV which corresponds to the atmospheric neutrino mass scale and the squared difference between \(m_3\) and \(m_2\) explain the solar mass scale. Thus, the \(U(1)_{B-L}\) breaking scale can be determined as \(v_{B-L} \simeq 3.0 \times 10^{14}\) GeV with taking the coupling constants unity. Note that we can reproduce the observed mixing angles in the MNS matrix by taking proper values of neutrino Yukawa couplings, \(y_{\alpha\beta}\).

### 3 Phenomenological consequence

We are at the position to reveal the required values for our model parameters by cosmological observations. We assume that all of the dimension-less coupling constants are unity just for simplicity and the cutoff scale is the reduced Planck scale, \(\Lambda = 2.4 \times 10^{18}\) GeV.

Firstly, we estimate the breaking scale of the extra symmetries by the mass of the lightest right-handed neutrino, \(M_1\), which comes from Eq. (10),

\[
M_1 \simeq \left(\frac{v_{FN}}{\Lambda}\right)^{2n} v_{B-L},
\]

(14)

#3We can also reproduce the inverted mass ordering case.
and the mixing angle can be represented as

$$\Theta^2 \simeq \left( \frac{(M_D)_{\alpha 1}}{M_1} \right)^2 \simeq \left( \frac{v_{\nu}^n v_{\text{DM}} / \Lambda^n}{v_{\nu}^{2n} v_{B-L} / \Lambda^{2n}} \right)^2 .$$

From the observations, each value is constrained as

$$M_1 = 7.06 \pm 0.05 \text{ keV},$$

$$\Theta^2 = (0.55 - 5.0) \times 10^{-11},$$

and here, we fix these as the best fit values as $M_1 = 7.06$ keV and $\Theta^2 = 1.3 \times 10^{-11}$.

We first mention to the scale of $v_{\text{DM}}$. One can rewrite Eq. (15) by the seesaw neutrino mass, $m_\nu$, as

$$\Theta^2 \simeq \left( \frac{v_{\text{DM}}}{v} \right)^2 \frac{m_\nu}{M_1} = 1.3 \times 10^{-11} .$$

This relation is free from the scale of $v_{\nu}$ and the charge $n$ and determines $v_{\text{DM}}$ as,

$$v_{\text{DM}} \simeq 0.17 \text{ GeV} .$$

This value can be explained when $|m_3/m_2| \simeq 3.1 \times 10^{-2}$ in Eq. (8) is realized.

Meanwhile, the remaining ambiguities of this model are the value of $v_{\nu}$ and $n$. These values are also determined by the constraint of the DM mass. The correlation between $v_{\nu}$ and $n$ is shown in the Fig. [1]. We concentrate the region of the breaking scale of $U(1)_{\nu}$ as $10^{15}$ GeV $\leq v_{\nu} \leq 10^{17}$ GeV to realize suitable fermion mass hierarchies. The cases $n = 1$ and $n = 2$ are not applicable because $v_{\nu}$ becomes out of the range.

We would like to give a brief comment on the production mechanism of the DM. One simple production mechanism is called the Dodelson-Widrow mechanism [43] in which RH$\nu$DM is
produced via mixing after the Big Bang Nucleosynthesis. However, the required magnitude of mixing angle for this mechanism is much larger than the experimental result. So, we need to consider other possibilities. One possibility is the production via B-L gauge boson s-channel exchange [44]. In this case, the relic abundance is evaluated as

\[
\Omega_{\nu_R} h^2 = 0.14 \left( \frac{M_1}{7 \text{ keV}} \right) \left( \frac{100}{g_*} \right)^{3/2} \left( \frac{T_R}{4.0 \times 10^{13} \text{ GeV}} \right)^3 \left( \frac{3.0 \times 10^{14} \text{ GeV}}{v_{B-L}} \right)^4 ,
\]

where \( h \) is the dimensionless Hubble parameter and \( T_R \) denotes the reheating temperature of the universe. When we adopt the thermal production, the data from from Lyman-\( \alpha \) forest [45]-[48] should be taken into account. However, this bound is well known to be relaxed by late time entropy dilution [49, 50]. The total amount of thermal abundance seems to become smaller than the Eq. (20), but we can adjust the abundance by controlling the reheating temperature. We skip the detailed estimation here. Moreover, in this set up, we can also explain the baryon asymmetry of the universe via so-called the leptogenesis scenario [51]. Therefore, the sufficient amount of the DM can also be explained in our setup. But the detail discussion of generated amount of the baryon asymmetry of the universe is beyond the scope of this paper.

4 Summary

We have discussed the extended model in which the right-handed neutrino dark matter included. It can explain the recent observed 3.5 keV X-ray signal by XMM-Newton observatory. One of the most impressive features of our model is the existence of the dark matter-philic Higgs field, \( H_{DM} \). The smallness of the mixing angle of the lightest right-handed neutrino is ensured by the smallness of the vacuum expectation value of this dark matter-philic Higgs field. On the other hand, the smallness of the mass of the dark matter can be realized by the Froggatt-Nielsen mechanism.

We have shown that the observation fixes the scale of \( v_{DM} \) as 0.17 GeV and the intriguing point is the uncertainty of this model to realize the DM mass is not essential to determine this scale.

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