Two Loop Radiative Seesaw and X-ray line Dark Matter

with

Global $U(1)$ Symmetry

Hiroshi Okada\textsuperscript{1,*}

\textsuperscript{1}School of Physics, KIAS, Seoul 130-722, Korea

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Abstract

We study a two loop induced radiative neutrino model with global $U(1)$ symmetry at 0.1 GeV scale, in which we consider a keV scale of dark matter candidate recently reported by XMN-Newton X-ray observatory using data of various galaxy clusters and Andromeda galaxy. We also discuss the vacuum stability of singly charged bosons, lepton flavor violation processes, and a role of Goldstone boson.

Keywords: Radiative seesaw, Goldstone Boson, X-ray Line

*Electronic address: hokada@kias.re.kr
TABLE I: Contents of lepton and scalar fields and their charge assignment under $SU(2)_L \times U(1)_Y \times U(1)$.

|                  | Lepton Fields | Scalar Fields |
|------------------|---------------|---------------|
| $SU(2)_L$        | $L_L$ $e_R$ $N_R$ | $\Phi$ $\chi^+_1$ $\chi^+_2$ $\varphi$ |
| $U(1)_Y$        | $-1/2$ $-1$ $0$ | $+1/2$ $+1$ $+1$ $0$ |
| $U(1)$          | $-x$ $-x$ $x/3$ | $0$ $2x$ $2x/3$ $-2x/3$ |

One of the promising scenarios simultaneously to explain between Neutrinos and dark matter (DM) physics is to generate neutrino masses at multi-loop level \[1\text{–}47\], \[48\text{–}61\], \[62\], in which DM could be a mediated field in the neutrino loop.

As for the DM sector, X-ray line signal at 3.55 keV from the analysis of XMM-Newton X-ray observatory data of various galaxy clusters and Andromeda galaxy \[63\text{,}64\] can be easily understood by decaying scenario, in which the DM mass be 7.1 keV and mixing angle between DM and the active neutrinos be $\sin^2 2\theta \approx 10^{-10}$. Due to these simple implications, many works have been studied \[61\text{,}65\text{–}109\].

In our paper, we propose a two loop induced radiative neutrino model with a global $U(1)$ symmetry, in which such a small mixing between DM and neutrinos can be generated at one-loop level. Observed relic density can be thermally obtained by the annihilation process with Goldstone boson (GB) final state that is the consequence of the global $U(1)$ symmetry.

This paper is organized as follows. In Sec. II, we show our model building including Higgs potential, neutrino masses. In Sec. III, we analyze DM properties including relic density and X-ray line. We conclude in Sec. VI.

II. MODEL SETUP

We discuss a two-loop induced radiative neutrino model. The particle contents and their charges are shown in Tab. II. We add three gauge singlet Majorana fermions $N_R$, two singly-charged singlet scalars $(\chi^+_1, \chi^+_2)$, and a neutral singlet scalar $\varphi$ to the SM. We assume
that only the SM-like Higgs $\Phi$ and $\varphi$ have vacuum expectation values (VEVs), which are symbolized by $v$ and $v'$ respectively. We also introduce a global $U(1)$ symmetry, under which $x \neq 0$ is an arbitrary number of the charge of $U(1)$ symmetry, and their assignments can realize our neutrino model at two loop level.

The relevant Lagrangian under these assignments are given by

$$\mathcal{L}_Y \simeq y_L L e_R + f_{ij} L_i^c \cdot L_j \chi_1^+ + g_{ij} \tilde{N}_R \epsilon^c_{Rj} \chi_2^- + \frac{1}{2} y_N \varphi \tilde{N}_R^c N_R + \lambda_0 \varphi^2 \chi_1^+ \chi_2^- + \text{h.c.}, \quad (I.1)$$

where the first term of $\mathcal{L}_Y$ can generates the SM charged-lepton masses, and we assume $\lambda_0$ to be real. The Majorana mass ($M_N \equiv y_N v'/\sqrt{2}$) can be generated after the spontaneous breaking of $\varphi$. The scalar fields can be parameterized as

$$\Phi = \left[ \begin{array}{c} w^+ \\ v + \phi + iz \end{array} \right], \quad \varphi = \frac{v' + \sigma}{\sqrt{2}} e^{i G/v'}, \quad (I.2)$$

where $v \simeq 246$ GeV is the VEV of the Higgs doublet, and $w^\pm$ and $z$ are respectively (non-physical) GB which are absorbed by the longitudinal component of $W$ and $Z$ boson. Since the CP even bosons ($\phi, \sigma$) and singly-charged bosons ($\chi_1^+, \chi_2^+$) mix each other through the term $|\Phi|^2 |\varphi|^2$ and $\varphi^2 \chi_1^+ \chi_2^-$ respectively, each of the resulting mass eigenstate and mixing matrix is reparametrized as [60]

$$\left[ \begin{array}{c} \sigma \\ \phi \end{array} \right] \equiv V^\dagger \left[ \begin{array}{c} h_1 \\ h_2 \end{array} \right], \quad \left[ \begin{array}{c} \chi_1^+ \\ \chi_2^- \end{array} \right] \equiv O^\dagger \left[ \begin{array}{c} h_1^+ \\ h_2^+ \end{array} \right], \quad (I.3)$$

where $h_2$ is the SM-like Higgs, $h_1$ is an additional CP-even Higgs mass eigenstate, $(h_1^+, h_2^+)$ is the singly charged boson mass eigenstate, and each of $O$ and $V$ is $2 \times 2$ unitary mixing matrix.

**Constraints for the charged bosons:** The vacuum stability should be satisfied for the pure quartic couplings of $\chi_{1,2}^+$. This condition up to the one-loop level can be given as

$$\lambda_a \simeq \lambda_{ha}^0 - \frac{3}{2(4\pi)^2} (v' X_{ba} + v Y_{ba})^4 \left[ \frac{(m_{h_a}^2 + m_{h_b}^2) \ln \left[ \frac{m_{h_a}^2}{m_{h_b}^2} \right]}{(m_{h_a}^2 - m_{h_b}^2)^3} \right]$$

$$+ \sum_{a,i,j,k,l} \frac{4 M_{N_j} M_{N_i}}{(4\pi)^2} \left( g_{k,i} a_a^i a_a^{j,l} a_{a}^l \right) \int \frac{da db dc dd \delta(a + b + c + d - 1)}{a m_{\ell_k}^2 + b m_{\ell_k}^2 + c M_{N_i}^2 + d M_{N_j}^2} \gtrsim 0, \quad (I.4)$$

$$\lambda_{ha} \equiv \lambda_{\chi_1} |O_{1a}|^4 + \lambda_{\chi_2} |O_{2a}|^4, \quad X_{ba} \equiv \frac{1}{2} V_{1b}^\dagger (\lambda_{\varphi \chi_1} |O_{1a}|^2 + \lambda_{\varphi \chi_2} |O_{2a}|^2), \quad (I.5)$$

$$Y_{ba} \equiv \frac{1}{2} V_{2b}^\dagger (\lambda_{\Phi \chi_1} |O_{1a}|^2 + \lambda_{\Phi \chi_2} |O_{2a}|^2), \quad (I.6)$$


where the trivial quartic coupling $\lambda_{h_1h_2}$ is defined to be the coefficient of $|h_1|^2|h_2|^2$. Here there exist two contributions; boson mediated one and fermion mediated one. 

A. Neutrino mass matrix

At first we redefine some terms in Lagrangian that can be replaced by the mass eigenstate as

$$\mathcal{L}_Y \sim f_{ij}(O^1)_{ja}L_L^c \cdot L_L h_a^- + g_{ij}(O^2)_{2a} N_R e_R c, h_a^- + \frac{y_N V_{1b}}{\sqrt{2}} h_b^0 N_R N_R + h.c.$$  

$$\equiv f_{ij} L_L^c \cdot L_L h_a^- + g_{ij} N_R e_R c, h_a^- + \frac{y_N^b}{2} h_b^0 N_R N_R + h.c.,$$  

where $f_{ij} \equiv f_{ij}(O^1)_{ja}$, $g_{ij} \equiv g_{ij}(O^2)_{2a}$, and $y_N V_{1b}/\sqrt{2} \equiv y_N^b$.

The dominant active neutrino mass matrix $m_\nu$ is then given at two-loop level by

$$(m_\nu)_{ij} = -(m_D)_{ik} M_N^{-1} (m_D)^T_{kj},$$  

$$(m_D)_{ik} = \frac{1}{(4\pi)^2} \sum_a \sum_{j=1}^{1-3} f_{ij}^a m_\ell_j g_{kj}^a \frac{\ln \epsilon_{aj}}{1 - \epsilon_{aj}},$$  

where $\epsilon_{aj} \equiv (m_\ell_j/m_{h_a^+})^2$, $M_N$ is diagonal, and $m_\ell = (m_e, m_\mu, m_\tau)$ is the charged-lepton mass that is also diagonal without loss of the generality.

Notice here another diagram with Zee-Babu like diagram can be tiny enough, since the maximum mass scale of the right-handed neutrino $N_R$ is expected to be $\mathcal{O}(100)$ MeV that comes from the analysis of X-ray DM as can be seen later. This formula can be found in the Appendix.

The observed mixing matrix; PMNS(Pontecorvo-Maki-Nakagawa-Sakata) matrix ($U_{PMNS}$) [110], can be realized by introducing the Casas-Ibarra parametrization [111] 2. In our case, the Dirac type Yukawa parameters can be given by

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1 The perturbativity and the avoiding the global minimum can be straightforwardly satisfied if each of quartic coupling does not exceeds $\pi$ and each of the sum of mass terms and the couplings is positive.

2 Even if the matrix is rank 2, this parametrization is adaptable [112].
To obtain the observed neutrino mass ($\approx 0.1$ eV), $\sum_a f^a g^{aT}$ can be estimated as $O(10^{-5})$, fixing $m_{h^+} \approx 100$ GeV and $M_N \approx 0.1$ GeV.

### B. Lepton Flavor Violations (LFVs)

1. $\ell_i^- \rightarrow \ell_j^+ \ell_k^- \ell_l^-$ process

   The constraints from the $\ell_i^- \rightarrow \ell_j^+ \ell_k^- \ell_l^-$ process can be given at one-loop level through $g$ term as

   \[
   \frac{4}{(4\pi)^2} \sum_{\alpha, \beta} \sum_{a, b}^{1-3} g_{a}^{g} g_{b}^{g} \left( g_{a}^{g} g_{b}^{g} - g_{a}^{g} g_{b}^{g} \right) \ln \left( \frac{m_{h^+}^{2}}{m_{h^+}^{0}} \right) \lesssim R(i^- \rightarrow j^+ k^- l^-) \left( \frac{m_{h^+}}{\text{TeV}} \right)^2, \quad (\text{II.12})
   \]

   where each of $R(i^- \rightarrow j^+ k^- l^-)$ is given by $R(\mu^- \rightarrow e^+ e^- e^-) \approx 2.3 \times 10^{-5}$, $R(\tau^- \rightarrow e^+ e^- e^-) \approx 0.009$, $R(\tau^- \rightarrow e^+ e^- \mu^-) \approx 0.005$, $R(\tau^- \rightarrow e^+ \mu^- \mu^-) \approx 0.007$, $R(\tau^- \rightarrow \mu^+ e^- e^-) \approx 0.007$, $R(\tau^- \rightarrow \mu^+ e^- \mu^-) \approx 0.007$, and $R(\tau^- \rightarrow \mu^+ \mu^- \mu^-) \approx 0.008$ [113].

   Here notice that the left-hand side is exactly zero if $k = l$. Hence a process such as $\mu^- \rightarrow e^+ e^- e^-$ (that provides the most stringent constraint; $R(\mu \rightarrow e e e) = 2.3 \times 10^{-5}$) does not give any constraints. The other processes constrain $g \lesssim O(0.1)$, when we fix $m_{h^+} \approx 100$ GeV.
2. $\ell_i/\ell_j$ universality

The constraint of the $\ell_i/\ell_j$ universality is given as

$$\sum_{a}^{1,2} |f_{ik}^a|^2 - |f_{jk}^a|^2 < R(\ell_i/\ell_j) \left( \frac{m_{h^+_1}}{\text{TeV}} \right)^2,$$  \hspace{1cm} (II.13)

where $i \neq j \neq k$, and each of $R(\ell_i/\ell_j)$ is given by $R(\mu/e) \approx 0.024$, $R(\tau/\mu) \approx 0.035$, and $R(\tau/e) \approx 0.04 \[113\]$. The processes constrain $f \lesssim O(0.01)$, when we fix $m_{h^+} \approx 100 \text{ GeV}.$

3. $\ell_i \to \ell_j \gamma$ process

The constraint of the $\ell_i \to \ell_j \gamma$ process is given as

$$\sum_{a,b}^{1,2} \left( r_{ab}^2 |f_{jk}^a|^2 + 16 |d_{jk}^{b*}g_{ki}^{b*}|^2 \right) < R(\ell_i \to \ell_j \gamma) \left( \frac{m_{h^+_1}}{\text{TeV}} \right)^2,$$  \hspace{1cm} (II.14)

where $i \neq j \neq k$, $r_{ab} \equiv (m_{h^+_b}/m_{h^+_a})^2$, and $R(\ell_i \to \ell_j \gamma)$ is given by $R(\mu \to e\gamma) \approx 1.6 \times 10^{-6}$ (that is the most stringent constraint), $R(\tau \to e\gamma) \approx 0.52$, and $R(\tau \to \mu\gamma) \approx 0.7 \[113\]. Then it constrains $(f, g) \lesssim O(0.01)$, when we fix $m_{h^+} \approx 100 \text{ GeV}$ and $f \approx g$.

Considering all these processes, $(f, g) \lesssim O(0.01)$ is obtained. But this constraint is milder than the one of neutrino mass scale estimation.

III. DARK MATTER

We have a fermionic DM candidate $X \equiv N_{R_1}$, which is assumed to be the lightest particle of $N_{R_i}$. However since $X$ decays into the SM particles ($\nu_L + \gamma$) at the one-loop level, heavier mass $\gtrsim O(1) \text{ GeV}$ cannot be allowed due to its too fast decay. Hence we focus on the explanation of the X-ray line at 3.55 keV. Then its mass $M_X \equiv M_{N_1}$ should be around 7.1 keV with small mixing $\theta$ between $X$ and the active neutrinos; $\theta \approx 5 \times 10^{-6}$. The observed relic density can be thermally generated through the process of the GB final state due to the global $U(1)$ symmetry.

Relic density: Due to the global symmetry, we have the annihilation process with the GB final state; $2X \to 2G$. Then the relativistic cross section of $X$ is given by

$$(\sigma v_{\text{rel}}) \approx \frac{M_X^4}{32 \pi \nu^2 (m_{h^+_1}^2 - 4M_X^2)^2} v_{\text{rel}}^2,$$  \hspace{1cm} (III.1)
FIG. 1: Allowed region between $v'$ and $m_{h_1}$ to satisfy the observed relic density $\Omega_X h^2 \approx 0.12$. It implies each of the allowed region can be $1.0 \times 10^{-3}$ GeV $\lesssim m_{h_1} \lesssim 3.8 \times 10^{-3}$ GeV, and $5.0 \times 10^{-3}$ GeV $\lesssim v' \lesssim 0.1$ GeV.

where we neglect the contribution of the SM Higgs $h_2$ and fix $|V_{11}|^4 \approx \mathcal{O}(1)$. To obtain the observed relic density $\Omega_X h^2 \approx 0.12$ [114], the cross section should be

$$(\sigma v)_{rel} \approx 2.6 \times 10^{-9} \text{ GeV}^{-2}.$$  

We plot the allowed region in terms of $v'$ and $m_{h_1}$ in Fig. 1 in which each of the allowed region can be obtained by $1.0 \times 10^{-3}$ GeV $\lesssim m_{h_1} \lesssim 3.8 \times 10^{-3}$ GeV, and $5.0 \times 10^{-3}$ GeV $\lesssim v' \lesssim 0.1$ GeV. Since the right-handed neutrino masses are generated through $v'$, the maximum mass value cannot exceed $\mathcal{O}(0.1)$ GeV. This is because the maximum value of $M_{N_i}$ is set to be 0.1 GeV.

The mixing $\theta$ between $X$ and the active neutrinos at one-loop level can be given by

$$\theta = \frac{(m_D)_{i1}}{M_X} \approx 5 \times 10^{-6} \rightarrow (m_D)_{i1} \approx 0.036 \text{ eV}.$$  

Although the above Dirac mass cannot generate a typical neutrino mass scale, we find a solution due to one massless neutrino in our model.

IV. CONCLUSIONS

We have constructed a two-loop induced neutrino model with a global $U(1)$ symmetry at 0.1 GeV scale, in which various LFV processes do not conflict with the explanation of the
keV scale DM recently reported by XMN-Newton X-ray observatory using data of various galaxy clusters and Andromeda galaxy. To explain such a DM candidate, we have found the following allowed ranges on the analysis of the observed relic density: $1.0 \times 10^{-3}$ GeV $\lesssim m_{h_1} \lesssim 3.8 \times 10^{-3}$ GeV, and $5.0 \times 10^{-3}$ GeV $\lesssim \nu' \lesssim 0.1$ GeV.

Appendix

The Zee-Babu type neutrino mass formula can be given by

$$
(m_\nu)_{nm} = -\sum_{a,b} \sum_{j,k,l} f_{aj}^a m_{\ell_j} g_{kj}^b M_{N_k} g_{kl}^a m_{\ell_l} f_{bm}^b,
$$

$$
\times \int dx dy dz \delta(x + y + z - 1) \int dx' dy' dz' \frac{\delta(x' + y' + z' - 1)}{(y^2 - y)y' X_{h_1}^+ - (y X_{N_k} + z X_{h_1}^+)} z',
$$

(IV.1)

where $X_f \equiv (m_f/M)^2$, and $M \equiv \text{Max}(m_{h_1}^+, m_{h_b}^+, M_{N_k}) \approx \text{Max}(m_{h_1}^+, m_{h_b}^+)$. The lower bound of the singly-charged boson can be obtained by the LEP experiment; $80$ GeV $\leq m_{h_1}$ [114]. When we fix the following scale in order to maximize the neutrino mass; $M \approx 80$ GeV, $M_{N} \approx 0.1$ GeV (that is expected to be the X-ray DM analysis), $(f^a g^b g^a f^b) \approx 10^{-9}$ that is required to generate the observed neutrino mass from the dominant contribution with $m_{\ell} \approx m_\tau = 1.777$ GeV. As a result, the the observed neutrino mass scale can be obtained at around $O(10^{-9})$ eV that can be negligible.

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