ILC phenomenology in a TeV scale radiative seesaw model for neutrino mass, dark matter and baryon asymmetry

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We discuss phenomenology in a new TeV scale model which would explain neutrino oscillation, dark matter, and baryon asymmetry of the Universe simultaneously by the dynamics of the extended Higgs sector and TeV-scale right-handed neutrinos. Tiny neutrino masses are generated at the three-loop level due to the exact $Z_2$ symmetry, by which the stability of the dark matter candidate is guaranteed. The model provides various discriminative predictions in Higgs phenomenology, which can be tested at the Large Hadron Collider and the International Linear Collider.

1 Introduction

In spite of the success of the Standard Model (SM) for elementary particles, it is widely understood that a new model beyond the SM must be considered to explain the phenomena such as tiny neutrino masses and their mixing \[1\], the nature of dark matter (DM) \[2\] and baryon asymmetry of the Universe \[3\].

We here discuss the model in which these problems would be simultaneously explained by the TeV-scale physics \[4\]. Tiny neutrino masses are generated at the three-loop level due to an exact discrete symmetry, by which tree-level Yukawa couplings of neutrinos are prohibited. The lightest neutral odd state under the discrete symmetry is a candidate of DM. Baryon asymmetry can also be generated at the electroweak phase transition (EWPT) by additional CP violating phases in the Higgs sector \[5\]. In this framework, a successful model can be made without contradiction of the current data.

The original idea of generating tiny neutrino masses via the radiative effect has been proposed by Zee \[6\]. The extension with a TeV-scale right-handed (RH) neutrino has been discussed in Ref. \[7\], where neutrino masses are generated at the three-loop level due to the exact $Z_2$ parity, and the $Z_2$-odd RH neutrino is a candidate of DM. This has been extended with two RH neutrinos to describe the neutrino data \[8\]. Several models with adding baryogenesis have been considered in Ref. \[9\]. The following advantages would be in the present model \[4\]: (a) all mass scales are at most at the TeV scale without large hierarchy, (b) physics for generating neutrino masses is connected with that for DM and baryogenesis, (c) the model parameters are strongly constrained by the current data, so that the model provides discriminative predictions which can be tested at future experiments.

In the following, we first explain the basic properties of the model, and discuss its phenomenology, in particular that at the International Linear Collider (ILC).
2 Model

Two scalar isospin doublets with hypercharge 1/2 (Φ_1 and Φ_2), charged singlet fields (S^±), a real scalar singlet (η) and two generation isospin-singlet RH neutrinos (N°_R with α = 1, 2) are introduced in our model [4]. We impose an exact Z_2 symmetry to generate tiny neutrino masses at the three-loop level, which we refer as Z_2. We assign Z_2-odd charge to S^±, η and N°_R, while ordinary gauge fields, quarks and leptons and Higgs doublets are Z_2 even. In order to avoid the flavor changing neutral current in a natural way, we impose another (softly-broken) discrete symmetry (˜Z_2) [10]. We employ so called Type-X Yukawa interaction [11], where ˜Z_2 charges are assigned such that only Φ_1 couples to leptons whereas Φ_2 does to quarks [12, 13, 14];

\[
L_Y = -y_e \bar{\ell}_i \Phi_1 e_R^i - y_u \bar{Q}_i \Phi_2 u_R^i - y_d \bar{Q}_i \Phi_2 d_R^i + h.c.,
\]

where \(Q^i (L^i)\) is the ordinary i-th generation left-handed (LH) quark (lepton) doublet, and \(u_R^i\) and \(d_R^i\) (\(e_R^i\)) are RH-singlet up- and down-type quarks (charged leptons), respectively.

We summarize the particle properties under Z_2 and ˜Z_2 in Table 1.

The Yukawa coupling in Eq. (1) is different from that in the minimal supersymmetric SM (MSSM) [15]. In addition to the usual potential of the two Higgs doublet model (THDM) with the ˜Z_2 parity and that of the Z_2-odd scalars, we have the interaction terms between Z_2-even and -odd scalars:

\[
L_{int} = -\sum_{a=1}^{2} \left( \rho_a |\Phi_a|^2 |S|^2 + \sigma_a |\Phi_a|^2 \frac{|S|^2}{2} \right) - \sum_{a,b=1}^{2} \left\{ \kappa \epsilon_{ab} (\Phi_a^* \Phi_b) S - \eta \right\} + h.c.,
\]

where \(\epsilon_{ab}\) is the anti-symmetric tensor with \(\epsilon_{12} = 1\). The mass term and the interaction for N°_R are given by

\[
L_{Y_N} = \sum_{a=1}^{2} \left\{ \frac{1}{2} m_{N_R^a} N_R^a N_R^a - h^\alpha_i (\Phi_R^* \Phi_R) N_R^a S + h.c. \right\}.
\]

Although the CP violating phase in the Lagrangian is crucial for successful baryogenesis at the EWPT [5], it does not much affect the following discussions. Thus, we neglect it for simplicity. We later give a comment on the case with the non-zero CP-violating phase.

As Z_2 is exact, the even and odd fields cannot mix. Mass matrices for the Z_2-even scalars are diagonalized as in the usual THDM by the mixing angles α and β, where α diagonalizes the CP-even states, and tan β = \(\langle \Phi_0^2 \rangle / \langle \Phi_0^1 \rangle\) [15]. The Z_2 even physical states are two CP-even (h and H), a CP-odd (A) and charged (H^±) states. We here define h and H such that h is always the SM-like Higgs boson when sin(β - α) = 1.

| \(Z_2\) (exact) | Q^ | u_R^ | d_R^ | L^ | e_R^ | Φ_1 | Φ_2 | S^± | η | N°_R |
|----------------|-----|------|------|----|------|-----|-----|-----|---|------|
| + + + + + +    | +   | +    | +    | +  | +    | +   | -   | -   | - | +    |
| Z_2 (softly broken) | +   | -    | -    | +  | +    | +   | -   | +   | + | +    |

Table 1: Particle properties under the discrete symmetries.
Figure 1: The diagrams for generating tiny neutrino masses.

| Set | $h_e^1$ | $h_e^2$ | $h_{\mu}^1$ | $h_{\mu}^2$ | $h_{\tau}^1$ | $h_{\tau}^2$ | $B(\mu \to e\gamma)$ |
|-----|---------|---------|-------------|-------------|-------------|-------------|----------------|
| A   | 2.0     | 2.0     | -0.020      | 0.0012      | -0.0025     | 1.5 x 10^{-12} |
| B   | 2.2     | 2.1     | 0.0087      | 0.037       | -0.0010     | 0.0021      | 7.8 x 10^{-12} |

Table 2: Values of $h_i^\alpha$ for $m_{H^\pm}(m_{S^\pm}) = 100$ (400) GeV, $m_\tau = 50$ GeV, $m_{N^\alpha_h} = m_{N^\alpha_\eta} = 3.0$ TeV for the normal hierarchy. For Set A (B), $\kappa \tan \beta = 29$ (34) and $U_{e3} = 0$ (0.14). Predictions on the branching ratio of $\mu \to e\gamma$ are also shown.

3 Neutrino Mass, Dark Matter, and Strongly 1st-Order Phase Transition

The LH neutrino mass matrix $M_{ij}$ is generated by the three-loop diagrams in Fig. 1. The absence of lower order loop contributions is guaranteed by $Z_2$. $H^\pm$ and $e^\pm_\kappa$ play a crucial role to connect LH neutrinos with the one-loop sub-diagram by the $Z_{2}$-odd states. We obtain

$$M_{ij} = \sum_{\alpha=1}^{2} C_{ij}^{\alpha} F(m_{H^\pm}, m_{S^\pm}, m_{N^\alpha_h}, m_\eta).$$

(4)

where $C_{ij}^{\alpha} = 4\kappa^2 \tan^2 \beta (y_{\alpha}^{SM} h_i^0)(y_{\alpha}^{SM} h_j^0)$ with $y_{\alpha}^{SM} = \sqrt{2} m_{\alpha}/v$ and $v \simeq 246$ GeV. The factor of the three-loop integral function $F(m_{H^\pm}, m_{S^\pm}, m_{N^\alpha_h}, m_\eta)$ includes the suppression factor of $1/(16\pi^2)^3$, whose typical size is $\mathcal{O}(10^3)$eV. Magnitudes of $\kappa \tan \beta$ as well as $F$ determine the universal scale of $M_{ij}$, whereas variation of $h_i^\alpha$ ($i = e, \mu, \tau$) reproduces the mixing pattern indicated by the neutrino data [1].

Under the natural requirement $h_i^\alpha \sim \mathcal{O}(1)$, and taking the $\mu \to e\gamma$ search results into account [10], we find that $m_{N^\alpha_h} \sim \mathcal{O}(1)$ TeV, $m_{H^\pm} \lesssim \mathcal{O}(100)$ GeV, $\kappa \tan \beta \gtrsim \mathcal{O}(10)$, and $m_{S^\pm}$ being several times 100 GeV. On the other hand, the LEP direct search results indicate $m_{H^\pm}$ (and $m_{S^\pm}$) $\gtrsim 100$ GeV [11]. In addition, with the LEP precision measurement for the $\rho$ parameter, possible values uniquely turn out to be $m_{H^\pm} \simeq m_H$ (or $m_A$) $\simeq 100$ GeV for $\sin(\beta - \alpha) \simeq 1$. Thanks to the Yukawa coupling in Eq. (1), such a light $H^\pm$ is not excluded by the $b \to s\gamma$ data [17]. Since we cannot avoid to include the hierarchy among $y_{\alpha}^{SM}$, we only require $h_i^\alpha y_i \sim \mathcal{O}(y_e) \sim 10^{-5}$ for values of $h_i^\alpha$. Our model turns out to prefer the normal hierarchy scenario. Several sets for $h_i^\alpha$ are shown in Table 2 with the predictions on the
branching ratio of $\mu \to e\gamma$ assuming the normal hierarchy\textsuperscript{4}.

The lightest $Z_2$-odd particle is stable and can be a candidate of DM if it is neutral. In our model, $N_\alpha^R$ must be heavy, so that the DM candidate is identified as $\eta$. When $\eta$ is lighter than the $W$ boson, $\eta$ dominantly annihilates into $b\bar{b}$ and $\tau^+\tau^-$ via tree-level $s$-channel Higgs ($h$ and $H$) exchange diagrams, and into $\gamma\gamma$ via one-loop diagrams. From their summed thermal averaged annihilation rate $\langle \sigma v \rangle$, the relic mass density $\Omega_\eta h^2$ is evaluated. Fig. 2(Left) shows $\Omega_\eta h^2$ as a function of $m_\eta$. Strong annihilation can be seen near $50$ GeV $\simeq m_H/2$ ($60$ GeV $\simeq m_h/2$) due to the resonance of $H$ ($h$) mediation. The data ($\Omega_{DM} h^2 \simeq 0.11$ \textsuperscript{2}) indicate that $m_\eta$ is around $40$-$65$ GeV.

The model satisfies the necessary conditions for baryogenesis \textsuperscript{3}. Especially, departure from thermal equilibrium can be realized by the strong first order EWPT. The free energy is given at a high temperature $T$ by

$$V_{eff}[\phi, T] = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + \ldots,$$

where $\phi$ is the order parameter. A large value of the coefficient $E$ is crucial for the strong first order EWPT with keeping $m_h \lesssim 120$ GeV. For sufficient sphaleron decoupling in the broken phase, it is required that $\textsuperscript{18}$

$$\frac{\phi_c}{T_c} \left( \approx \frac{2E}{\lambda_T} \right) \gtrsim 1,$$

where $\phi_c$ ($\neq 0$) and $T_c$ are the critical values of $\phi$ and $T$ at the EWPT. In Fig. 2(Right), the allowed region under the condition of Eq. (6) is shown. The condition is satisfied when $m_{S^\pm} \gtrsim 350$ GeV for $m_A \gtrsim 100$ GeV, $m_h \simeq 120$ GeV, $m_H \simeq m_{H^\pm} (\simeq M) \simeq 100$ GeV and $\sin(\beta - \alpha) \simeq 1$, where $M$ represents the soft-breaking mass of extra Higgs bosons for $\tilde{Z}_2$ \textsuperscript{4}.

\textsuperscript{a}The predictions for $\mu \to e\gamma$ shown here are corrected ones from those in Ref. \textsuperscript{4}.
4 Phenomenology

A successful scenario which can simultaneously solve the above three issues under the data would be

$$\sin(\beta - \alpha) \simeq 1, \quad \kappa \tan \beta \simeq 30, \quad m_h = 120 \text{ GeV}, \quad m_H \simeq m_{H^\pm} \simeq \mathcal{O}(100) \text{ GeV},$$

$$m_A \gtrsim \mathcal{O}(100) \text{ GeV}, \quad m_{S^\pm} \sim 400 \text{ GeV}, \quad m_\eta \lesssim m_W, \quad m_{N^\pm_h} \simeq m_{N^\pm_R} \simeq 3 \text{ TeV}. \quad (7)$$

This is realized without assuming unnatural hierarchy among the couplings. All the masses are between $\mathcal{O}(100)$ GeV and $\mathcal{O}(1)$ TeV. The discriminative properties of this scenario are in order:

(I) $h$ is the SM-like Higgs boson, but decays into $\eta \eta$ when $m_\eta < m_h/2$. The branching ratio is about 30% for $m_\eta \simeq 43$ GeV and $\tan \beta = 10$. This is related to the DM abundance, so that our DM scenario is testable at the CERN Large Hadron Collider (LHC) and the ILC by searching the missing decay of $h$. Furthermore, $\eta$ is potentially detectable by direct DM searches, because $\eta$ can scatter with nuclei via the scalar exchange.

(II) For successful baryogenesis, the $hhh$ coupling has to deviate from the SM value by more than 10-20% (see Fig. 2), which can be tested at the ILC.

(III) $H$ (or $A$) can predominantly decay into $\tau^+\tau^-$ instead of $b\bar{b}$ for $\tan \beta \gtrsim 2$ because of the Type-X Yukawa interaction. For example, we have $B(H(A) \to \tau^+\tau^-) \simeq 100\%$ and $B(H(A) \to \mu^+\mu^-) \simeq 0.3\%$ for $m_A = m_H = 130$ GeV, $\sin(\beta - \alpha) = 1$ and $\tan \beta = 10$. The scenario with light $H^\pm$ and $H$ (or $A$) can be directly tested at the LHC via $pp \to W^* \to HH^\pm$ and $AH^\pm$, and also $pp \to HA$. Their signals are four lepton states $\ell^-\ell^+\tau^\pm\nu$ and $\ell^-\ell^+\tau^+\tau^-$, where $\ell$ represents $\mu$ and $\tau$.

(IV) The physics of $Z_2$-odd charged singlet $S^\pm$ is important to distinguish this model from the other new physics candidates. In Fig. 3 the production rate of the $e^+e^- \to HA$ is shown for $m_A = m_H$. For $\sqrt{s} = 500$ GeV, about 17,000 (110) of the $\tau^+\tau^-\tau^+\tau^-$ ($\mu^+\mu^-\tau^+\tau^-$) events are then produced from the signal for $m_A = m_H = 130$ GeV, while about 60 (0) events are in the MSSM for the similar parameter set. The main background comes from $ZZ$ production (about 400 fb), which is expected to be easily reduced by appropriate kinematic cuts.

The physics of $Z_2$-odd charged singlet $S^\pm$ is important to distinguish this model from the other models. At the LHC, they are produced in pair via the Drell-Yuan process.
The cross section amounts to 0.5 fb for $m_{S^\pm} = 400$ GeV at $\sqrt{s} = 14$ TeV, so that more than a hundred of the $S^+ S^-$ events are produced for the integrated luminosity 300 fb$^{-1}$. The produced $S^\pm$ bosons decay as $S^\pm \to H^\pm \eta$, and $H^\pm$ mainly decay into $\tau^\pm \nu$. The signal would be a high-energy hadron pair with a large missing transverse momentum.

The charged singlet scalar bosons $S^\pm$ in our model can also be better studied at the ILC via $e^+ e^- \to S^+ S^-$ shown in Fig. [4]. The total cross sections are shown as a function of $m_{S^\pm}$ for $\sqrt{s}$ in Fig. [5]. The other relevant parameters are taken as $m_{N_1^R} = m_{N_2^R} = 3$ TeV and $h_0 = h_2 = 2.0$. Both the contributions from the s-channel gauge boson ($\gamma$ and $Z$) mediation and the t-channel RH neutrino mediation are included in the calculation. The total cross section can amount to about 200 fb for $m_{S^\pm} = 400$ GeV at $\sqrt{s} = 1$ TeV due to the contributions of the t-channel RH neutrino-mediation diagrams with $O(1)$ coupling constants $h_0^\alpha$. The signal would be a number of energetic tau lepton pairs with large missing energies. Although several processes such as $e^+ e^- \to W^+ W^-$ and $e^+ e^- \to H^+ H^-$ can give backgrounds for this final state, we expect that the signal events can be separated by kinematic cuts.

Finally, there is a further advantage in testing our model at the $e^- e^-$ collision option of the ILC, where the dimension five operators $\ell^- \ell^- S^+ S^-$, which appear in the sub-diagram of the three-loop induced masses of neutrinos in our model, can be directly measured. The production cross section for $e^- e^- \to S^- S^-$ [t-channel $N_1^R$ mediation: see Fig. [6]] is given by

$$\sigma(e^- e^- \to S^- S^-) = \int_{t_{\text{min}}}^{t_{\text{max}}} dt \frac{1}{128 \pi s} \left| \sum_{\alpha=1}^{2} (|h_{0\alpha}|^2 m_{N_\alpha^R}) \left( \frac{1}{t-m_{N_\alpha^R}^2} + \frac{1}{u-m_{N_\alpha^R}^2} \right) \right|^2. \quad (8)$$

Due to the structure of our model that the tiny neutrino masses are generated at the three-loop level, the magnitudes of $h_{0\alpha}$ ($\alpha = 1, 2$) are of $O(1)$, by which the cross section becomes very large. Furthermore, thanks to the Majorana nature of the t-channel diagram we obtain much larger cross section in the $e^- e^-$ collision than at the $e^+ e^-$ collision when $m_{N_1^R}^2 \gg s$. Fig. [5] shows the production cross sections for $e^- e^- \to S^- S^-$ via the t-channel RH-neutrino. The cross section can be as large as 30 pb for $m_{S^\pm} = 400$ GeV for $\sqrt{s}_{e^- e^-} = 1$ TeV, $m_{N_1^R} = m_{N_2^R} = 3$ TeV and $h_0 = h_2 = 2.0$. The backgrounds are expected to be much less than the $e^+ e^-$ collision.
We emphasize that a combined study for these processes would be an important test for our model, in which neutrino masses are generated at the three-loop level by the $Z_2$ symmetry and the TeV-scale RH neutrinos.$^b$

In the other radiative seesaw models in which the neutrino masses are induced at the one-loop level with RH neutrinos, the corresponding coupling constants to our $h^\alpha_i$ couplings are necessarily one or two orders of magnitude smaller to satisfy the neutrino data, so that the cross section of the t-channel RH neutrino mediation processes are small due to the suppression factor $(h_\alpha^\mu)^4$.

(V) The couplings $h^\alpha_i$ cause lepton flavor violation such as $\mu \rightarrow e\gamma$ which would provide information on $m_{N_\alpha}$ at future experiments.

Finally, we comment on the case with the CP violating phases. Our model includes the THDM, so that the same discussion can be applied in evaluation of baryon number at the EWPT $^5$. The mass spectrum would be changed to some extent, but most of the features discussed above should be conserved with a little modification.

5 Summary

We have discussed the model with the extended Higgs sector and TeV-scale RH neutrinos, which would explain neutrino mass and mixing, DM and baryon asymmetry by the TeV scale physics. It gives specific predictions on the collider phenomenology. In particular, the predictions on the Higgs physics are completely different from those in the MSSM, so that the model can be distinguished at the LHC and also at the ILC.

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$^b$Unlike our model, in the model in Ref. 4, the coupling constants corresponding to our $h^\alpha_i$ are small and instead those to $h_\mu^\mu$ are $\mathcal{O}(1)$, so that its Majorana structure is not easy to test at $e^-e^-$ collisions.
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