Beyond the SM phenomena and the extended Higgs sector based on the SUSY
gauge theory with confinement

T. Shindou

Department of Applied Physics, School of Advanced Engineering,
Kogakuin University, Tokyo 163-8677, JAPAN

We propose a fundamental theory whose low-energy effective theory provides a phenomenological
description of electroweak baryogenesis, radiative neutrino mass generation, and dark matter. The
model is based on SUSY SU(2)_H gauge theory with confinement, and the model contains new Z_2
discrete symmetry and Z_2-odd right-handed neutrino superfields. The Higgs sector in the low energy
effective theory of this model below confinement scale is described by fifteen mesonic superfields of
fundamental SU(2)_H doublets. We present a benchmark scenario of this model, where all the
constraints from the current neutrino, dark matter, lepton flavour violation and LHC data are
satisfied. We also discuss how to test the scenario by the future collider experiments.

I. INTRODUCTION

Though the standard model (SM) is established by the discovery of the SM-like Higgs boson, new physics
beyond the SM are still required for solving several serious problems such as a mechanism to produce the baryon
asymmetry of the Universe (BAU), a origin of tiny neutrino masses, and a candidate of the dark matter (DM),
It is interesting to focus on the scenarios which solves these three problems at around the TeV scale, i.e. the
electroweak baryogenesis[1] for the mechanism for producing BAU, radiative seesaw scenarios for the origin of
tiny neutrino masses, and introducing weak interacting massive particles as candidates of the DM. Many nice
models in such a direction have been developed in literature. In particular, the Aoki-Kanemura-Seto (AKS)
model[4] is an attractive example which includes all the three mechanisms.
However, in the AKS model, it is known that a Landau pole appears at the scale much below the Planck
scale. It means that there should be a more fundamental theory above a cutoff scale. In the following, we
review a candidate of such a fundamental theory proposed in Refs. [2, 3], which is based on a supersymmetric (SUSY) gauge theory with confinement.

II. THE MODEL

It is known that confinement occurs in the SU(N_c) SUSY gauge theory with N_f flavours when N_f = N_c + 1
is satisfied[5]. The simplest case is N_c = 2 and N_f = 3. We utilize this simplest setup and propose a SUSY
SU(2)_H gauge theory\(^1\) in order to forbid tree level contributions to neutrino masses, an unbroken
Z_2 symmetry is introduced to the model. We also introduce a right-handed neutrino (RHN) superfield which has odd number
under the Z_2 symmetry. The assignment of the SM charge and the
Z_2-parity on the SU(2)_H doublets and the
RHN is shown in Table I-(I).

In this framework, the SU(2)_H gauge coupling becomes strong at a certain scale Λ_H, and the low energy
effective theory below Λ_H is described in terms of the fifteen mesonic fields listed in the Table I-(II), where
the mesonic superfields are canonically normalized as
\[ H_{ij} \approx \frac{1}{4\pi\Lambda_H} T_i T_j (i \neq j). \]

The superpotential of the Higgs
sector in the low energy effective theory can be written as
\[ W_{\text{eff}} = \lambda N (H_u H_d + v_0^2) + \lambda N (\Phi_u \Phi_d + v_0^2) + \lambda N (\Omega + \Omega - \zeta \eta + v_1) + \lambda \{ \zeta H_u \Phi_u + \eta H_d \Phi_d - \Omega + H_u \Phi_d - \Omega - H_u \Phi_u - N N \Omega \}. \]

It is naively expected that λ ≃ 4π at the confinement scale Λ_H. The relevant part of the soft SUSY breaking

\(^1\) It’s the same setup as the minimal SUSY fat Higgs model[6]. In the minimal SUSY fat Higgs model, only H_u, H_d, and N are
made light by introducing additional fields. On the other hand, all the mesonic fields listed in Table I-(II) play an important role
in our model.
TABLE I: (I) The charge assignment under the SM gauge group \((SU(3)_c \times SU(2)_L \times U(1)_Y)\) and the \(Z_2\) parity on the \(SU(2)_R\) doublets \(T_i\) and the RHN \(N_R\). (II) The field content of the extended Higgs sector or the low energy effective theory of the SUSY \(SU(2)_H\) model.

| Superfield | \(SU(2)_H\) | \(SU(3)_c\) | \(SU(2)_L\) | \(U(1)_Y\) | \(Z_2\) |
|-----------|-------------|-------------|-------------|------------|--------|
| \(T_1\)   | 2           | 1           | 2           | 0          | +1     |
| \(T_2\)   | 1           | 2           | 1           | 0          | +1     |
| \(T_3\)   | 2           | 1           | 1           | +1/2       | +1     |
| \(T_4\)   | 2           | 1           | 1           | -1/2       | +1     |
| \(T_5\)   | 2           | 1           | 1           | +1/2       | -1     |
| \(T_6\)   | 2           | 1           | 1           | -1/2       | -1     |
| \(N_R\)   | 1           | 1           | 1           | 0          | -1     |

\[
\mathcal{L}_H = -m^2_{H_u} H_u^2 - m^2_{H_d} H_d^2 - m^2_{\Phi_u} \Phi_u^2 - m^2_{\Phi_d} \Phi_d^2 - m^2_N N^2 - m^2_{N_R} N_R^2 N_R - m^2_{N_t} N_t^2 N_t
\]

\[
- \left\{ C \lambda v^2 N + C \lambda v^2 N_R + C \lambda v^2 N_t + \text{h.c.} \right\} - \left\{ B \mu H_u H_d + B \Phi \Phi_u \Phi_d + B \lambda \Omega \Omega + \text{h.c.} \right\} - \lambda \{ A N H_u H_d N + A \Phi_u \Phi_d N_R + A N_t \Omega \Omega \Omega \} + A \Phi_u H_u \Phi_d \Phi_d \Phi_d + A \Omega_+ \Phi_u \Phi_d \Phi_d \Phi_d + \text{h.c.} \right\}.
\]

After the \(Z_2\)-even neutral fields \(N, N_R\) and \(N_t\) get vacuum expectation values (vev’s), the mass parameters \(\mu = \lambda(N), \mu_\Phi = \lambda(\Phi_N)\) and \(\mu_\Omega = \lambda(\Omega_N)\) are induced.

The Yukawa couplings and the Majorana mass term of the RHN are given by

\[
W_N = y_N^i N_R^i L_i \Phi_u + h_N N_R^i E_i \Omega_+ + \frac{M_R}{2} N_R^i N_R^j + \frac{\kappa}{2} N_R^i N_R^j N_R^j.
\]

III. BENCHMARK POINTS AND ITS PREDICTIONS

In the low energy effective theory of the model, the first order electroweak phase transition (1stOPT) can be enhanced by the loop contributions of extra \(Z_2\)-odd scalar particles such as \(\Phi_u\) and \(\Omega_\) strongly enough to satisfy the condition \(\varphi_c/T_c > 1\), which is necessary for successful electroweak baryogenesis. Here, we focus only on the 1stOPT. In order to reproduce the BAU, we should also require new CP violating phases. We expect that we can introduce several new CP phases which contribute to the baryogenesis as in the case of MSSM[7].

Tiny neutrino masses are generated at loop levels as shown in Fig. 1. The one-loop diagrams are driven by the neutrino Yukawa coupling \(y_N\) and the three-loop diagrams are controlled by the coupling \(h_N^i\). Because of this, two different mass squared differences are explained even if only one RHN is introduced.

Since both \(Z_2\)-parity and \(R\)-parity are unbroken in our model, there can be three kinds of the DM candidates, i.e. the lightest particles with the parity assignments of \((- , +), (+, -), \) and \((- , -).\) If one of these three particle is heavier than the sum of the masses of the others, the heaviest one decays and only the other two can be DM.

In the Table II, we list the definition of a benchmark scenario and its predictions, where the condition \(\varphi_c/T_c > 1\) is satisfied, the neutrino masses and the mixing angles given by neutrino oscillation data can be
reproduced, and the relic abundance of the DM can be explained with satisfying the constraints from the experiments such as LFV searches and the direct detection of the DM.

FIG. 1: (I) A one-loop and (II) three-loop diagrams which contribute to the neutrino mass matrix. The figures are taken from [2]

In the benchmark scenario, the splitting between the charged Higgs boson and the \( Z \) is enhanced by the loop effect of \( \Phi_u \) and \( \eta \), which can also significantly affect the \( h-\gamma-\gamma \) coupling and the triple Higgs boson coupling as shown in Table III. By precise measurement at future collider experiment such as ILC[8] of such the Higgs boson couplings, our benchmark scenario can be

**TABLE II**: (i) The definition of our benchmark scenario, and (ii) its predictions. The tables are taken from Ref. [2].

(i) Input parameters for the benchmark scenario

| Parameter | Value |
|-----------|-------|
| \( \lambda \), tan \( \beta \), and \( \mu \)-terms | \( \lambda = 1.8 \) (\( \Lambda_H = 5 \) TeV) \( \tan \beta = 15 \) \( \mu = 250 \) GeV \( \mu_\Phi = 550 \) GeV \( \mu_\Omega = -550 \) GeV |
| \( Z_2 \)-even Higgs sector | \( m_h = 126 \) GeV \( m_{h^\pm} = 990 \) GeV \( m_\chi^0 = (1050 \) GeV\(^2 \) \( A_N = 2900 \) GeV |
| \( Z_2 \)-odd Higgs sector | \( m_{\tilde{\chi}^0_n} = m_{\tilde{\chi}^0_{\Omega_n}} = (175 \) GeV\(^2 \) \( m_{\tilde{\chi}^\pm_n} = m_{\tilde{\chi}^\pm_{\Omega_n}} = (1500 \) GeV\(^2 \) \( m_{\tilde{\chi}^0} = (2000 \) GeV\(^2 \) |
| RH neutrino and RH sneutrino sector | \( m_{\nu_R} = 63 \) GeV \( m_{\tilde{\nu}_R} = 65 \) GeV \( \kappa = 0.9 \) |
| Other SUSY SM parameters | \( y_N = (3.28 i, 6.70 i, 1.72 i) \times 10^{-6} \) \( h_N = (0, 0.227, 0.0204) \) |
| \( m_{\tilde{\chi}^\pm} = 500 \) GeV \( m_{\tilde{\nu}} = m_{\tilde{\nu}_\tau} = 5 \) TeV |

(ii) Predictions of the Benchmark points

| Effect | Value |
|--------|-------|
| Non-decoupling effects | \( \varphi_c/T_c = 1.3 \) \( \lambda_{hhb}/\lambda_{hbh} = 1.2 \) \( B(h \rightarrow \gamma \gamma)/B(h \rightarrow \gamma \gamma)_{\text{SM}} = 0.78 \) |
| Neutrino masses and the mixing angles | \( (m_1, m_2, m_3) = (0, 0.0084 \) eV\( , 0.0050 \) eV\) \( \sin^2 \theta_{12} = 0.32 \) \( \sin^2 \theta_{23} = 0.50 \) \( |\sin \theta_{13}| = 0.14 \) |
| LFV processes | \( B(\mu \rightarrow e\gamma) = 3.6 \times 10^{-13} \) \( B(\mu \rightarrow eee) = 5.6 \times 10^{-16} \) |
| Relic abundance of the DM | \( \Omega_{\nu_R} h^2 = 0.055 \) \( \Omega_{\tilde{\chi}^0} h^2 = 0.065 \) \( \Omega_{\text{DM}} h^2 = \Omega_{\nu_R} h^2 + \Omega_{\tilde{\chi}^0} h^2 = 0.12 \) |
| Spin-independent DM-proton scattering cross sections | \( \sigma^{SI}_{\nu_R} = 3.1 \times 10^{-46} \) cm\(^2 \) \( \sigma^{SI}_{\tilde{\chi}^0} = 7.7 \times 10^{-47} \) cm\(^2 \) \( \sigma^{SI}_{\text{DM}} = 1.1 \times 10^{-46} \) cm\(^2 \) |

In Fig. 2, we show the mass spectrum of the relevant particles in the benchmark scenario given in Table II. In this scenario, the \( Z_2 \)-even sector is similar to the nMSSM which can be distinguished from the MSSM by the spectrum of extra Higgs bosons. For example, the mass splitting between the charged Higgs boson and the heavy Higgs bosons is caused by the large mixing between doublet fields and a singlet field, which is necessary in order to reproduce the relic abundance of the DM.
distinguished from nMSSM. In addition, the direct search of inert doublet particles[9] and inert charged singlet searches[10] at ILC can also provide a strong hint on the $Z_2$-odd sector of the scenario.

IV. SUMMARY

We have attempted to propose a simple model to explain the three problems such as baryogenesis, tiny neutrino mass, and DM in its low energy effective theory and we have succeeded to find such a model based on SUSY SU(2)$_H$ gauge theory with confinement. We have introduced a benchmark scenario and we have discussed how to test it at future collider experiments.

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[1] V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B 155 (1985) 36; A. G. Cohen, D. B. Kaplan and A. E. Nelson, Ann. Rev. Nucl. Part. Sci. 43 (1993) 27; M. Quiros, Helv. Phys. Acta 67 (1994) 451; V. A. Rubakov and M. E. Shaposhnikov, Usp. Fiz. Nauk 166 (1996) 493 [Phys. Usp. 39 (1996) 461]; K. Funakubo, Prog. Theor. Phys. 96 (1996) 475; M. Trodden, Rev. Mod. Phys. 71 (1999) 1463; W. Bernreuther, Lect. Notes Phys. 591 (2002) 237; J. M. Cline, hep-ph/0609145; D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys. 14 (2012) 125003.

[2] S. Kanemura, N. Machida and T. Shindou, Phys. Lett. B 738 (2014) 178

[3] S. Kanemura, T. Shindou and T. Yamada, Phys. Rev. D 86 (2012) 055023; S. Kanemura, E. Senaha, T. Shindou and T. Yamada, JHEP 1305 (2013) 066; S. Kanemura, N. Machida, T. Shindou and T. Yamada, Phys. Rev. D 89 (2014) 1, 013005.

[4] M. Aoki, S. Kanemura and O. Seto, Phys. Rev. Lett. 102 (2009) 051805; M. Aoki, S. Kanemura and O. Seto, Phys. Rev. D 80 (2009) 033007; M. Aoki, S. Kanemura and K. Yagyu, Phys. Rev. D 83 (2011) 075016.

[5] K. A. Intriligator and N. Seiberg, Nucl. Phys. Proc. Suppl. 45BC (1996) 1.

[6] R. Harnik, G. D. Kribs, D. T. Larson and H. Murayama, Phys. Rev. D 70 (2004) 015002.

[7] M. Dine, P. Huet, R. L. Singleton, Jr and L. Susskind, Phys. Lett. B 257 (1991) 351; A. G. Cohen and A. E. Nelson, Phys. Lett. B 297 (1992) 111.

[8] H. Baer, T. Barklow, K. Fujii, Y. Gao, A. Hoang, S. Kanemura, J. List and H. E. Logan et al., arXiv:1306.6352 [hep-ph]; D. M. Asner, T. Barklow, C. Calancha, K. Fujii, N. Graf, H. E. Haber, A. Ishikawa and S. Kanemura et al., arXiv:1310.0763 [hep-ph].

[9] M. Aoki, S. Kanemura and H. Yokoya, Phys. Lett. B 725 (2013) 302.

[10] M. Aoki and S. Kanemura, Phys. Lett. B 689 (2010) 28.