PRAMANA — journal of physics

Vol. 86, No. 2
February 2016
pp. 223–229

Prospects of experimentally reachable beyond Standard Model physics in inverse see-saw motivated $SO(10)$ GUT

RAM LAL AWASTHI[1,2]
[1]Harish-Chandra Research Institute, Chhatnag Road, Jhunsi, Allahabad 211 019, India
[2]CETMS, Siksha 'O' Anusandhan University, Khandagiri Square, Bhubaneswar 751 030, India
E-mail: awasthi.r6@gmail.com

DOI: 10.1007/s12043-015-1142-1; ***e*Publication:** 6 January 2016

Abstract. The grand unification theories based on $SO(10)$ gauge group have been at the centre of attraction to beyond Standard Model phenomenology. The $SO(10)$ gauge symmetry may pass through several intermediate symmetries before breaking to Standard Model. Therefore some higher symmetries may occur at the experimentally reachable scales. This feature flourishes easily in non-supersymmetric models compared to supersymmetric ones. We find that certain breaking chains give tremendous predictions for the physics being explored at various particle physics experiments. Explanation to neutrino masses through TeV scale inverse see-saw is the driving theme of the models studied.

Keywords. Unification; inverse see-saw; $0\nu\beta\beta$ decay; lepton flavour violation; proton lifetime; $n-\bar{n}$ oscillation; K-decay; Z'-boson; sterile neutrinos.

PACS Nos 12.10.−g; 12.10.Dm; 12.10.kt; 12.60.−i

1. Introduction

The quest of a decent quantum field theoretic framework to describe the fundamental behaviour of the newly discovered particles and their strange interactions, during the first half of the 20th century, was culminated with the introduction of Standard Model (SM) of particle physics in 1967−68. Since then, the theory has been experimentally verified to a large accuracy in various collider experiments including the Large Hadron Collider (LHC) at CERN. All the particles predicted by the SM have not only been discovered but they also fit perfectly in the model framework.

Despite the fact that SM has unravelled the gauge origin of fundamental forces and the structure of Universe while successfully confronting numerous experimental tests, it has various limitations. For a good summary on its excellencies and compulsions see [1], and for extensive details on SM and beyond, see [2]. Currently, serious attempts are being made to probe (a) supersymmetry (SUSY) at LHC [3,4], (b) dark matter candidate in the galactic or extra galactic sources [5–9], (c) lepton number and flavour violation in flavour violating processes [10–12], (d) Dirac or Majorana nature of neutrinos in neutrinoless double beta decay experiments [13–20], (e) the hierarchy of light neutrino masses and CP-violating phases at neutrino oscillation experiments [21,22], (f) proton lifetime at Super-K experiments [23], (g) the rare decay of mesons [24,25], (h) possible n–$\bar{n}$ oscillation [26], and (i) any exotic particle signature of beyond SM physics at LHC [27,28] and Tevatron, including larger gauge structure or see-saw signature.

The SUSY extensions of SM, with SUSY restoration at TeV scale, solves the gauge hierarchy problem and unifies the gauge couplings around $10^{16.25}$ GeV. The minimal supersymmetric Standard Model can be further extended to incorporate the tiny masses of neutrinos and their mixings through see-saw paradigm. In models with R-parity conservation, the lightest SUSY particle which is stable and weakly interacting, can be a possible candidate for cold dark matter [29] of the Universe. Hence, the SUSY grand unified theories (GUTs) provide a very attractive framework for representing particles and forces [30]. An evidence of SUSY at the LHC would be a ground-breaking discovery deciding the future course of particle physics. But, in the absence of any evidence of SUSY so far, it is worthwhile to explore new physics prospects of non-SUSY GUTs.

2. Models and predictions

The $SO(10)$ group unifies all fermions of one generation including the right-handed (RH) neutrino into a single spinorial representation. It provides spontaneous origins of P and CP violations. Light neutrino and other SM fermion masses and mixings fit well. Although gauge couplings automatically unify in one-step breaking of SUSY $SO(10)$, they fail to unify in non-SUSY GUTs. But, once the intermediate symmetries are invoked to populate the grand desert in non-SUSY $SO(10)$, they unify. Certain intermediate gauge symmetries may also arise near the collider search scale. We found that all the minimal models with two-step breaking chains predict the intermediate gauge symmetries at very high energies which cannot be explored directly.

We, therefore, investigated the $n \geq 3$ step breaking chains [31] with the prospects of TeV scale inverse see-saw [32]. Thus, this mechanism has the potential to be experimentally verified. Its implementation requires an additional $SO(10)$ singlet fermion per generation. This introduces a new mass scale μ_S in the theory. The TeV-scale see-saw requires $\mu_S \sim$keV. In a theory with exact lepton number conservation $\mu_S = 0$, guaranteeing the masslessness of the left-handed (LH) neutrinos.

In three-step breaking, we found one such breaking scheme [33]

$$SO(10) \xrightarrow[45_H]{10^{15.5}\ \text{GeV}} G_{2_L 2_R 1_{B-L} 3_C} \xrightarrow[45_H]{10^{11.2}\ \text{GeV}} G_{2_L 1_R 1_{B-L} 3_C} \xrightarrow[16_H]{\text{TeV}} \text{SM}, \tag{1}$$

where breaking scales and the $SO(10)$ representation which contain the singlet of the nascent subgroups are shown above and below the arrows, respectively. The breaking of $SO(10)$ to left–right (LR) symmetry G_{2213} is realized at GUT scale by assigning vacuum expectation value (VEV) to the D-parity odd singlet of 45_H. Assigning VEV to RH triplet $(1, 3, 0, 1) \subset 45_H$ in singlet direction of G_{2113} symmetry breaks LR symmetry at intermediate scale whereas the breaking of G_{2113} to SM is achieved by assigning VEV to $(1, 1/2, -1/2, 1)$ of 16_H at TeV scale. Mass assignment to the scalars follow the extended survival hypothesis and thus the model is minimal in particle content. Though the $W_R^{\pm}$ gauge bosons are implausible at collider searches, the low mass ($\sim$ TeV) neutral gauge boson Z' and the associated non-unitarity effects of the TeV-scale inverse see-saw are the testable features of the model. The relevant Yukawa Lagrangian is

$$\begin{aligned}\mathcal{L}_{\text{Yuk}} &= Y^a 16.16.10_H^a + Y_\chi 16.1.16_H^\dagger + \mu_S 1.1 \\ &\ni Y_\nu \bar{l_L} N \phi_u + Y_\chi \bar{N} S \chi_R + \mu_S S^T S + \text{h.c.},\end{aligned} \tag{2}$$

which gives full inverse see-saw mass matrix with $M_D = Y_\nu \langle \phi_u \rangle$, $M = Y_\chi \langle \chi_R \rangle$ and μ_S as the elements of the matrix. The matrix M_D is determined by iterative renormalization group evolution (RGE) of low-energy data to GUT scale, using $SO(10)$ symmetry constraints and coming back to TeV scale to match the data. The matrix M is constrained using the non-unitarity constraints [34]. Light neutrinos acquire masses from inverse see-saw formula $[m_\nu = (M_D M^{-1}) \mu_S (M_D M^{-1})^T]$ and the heavy neutrinos get the quasi-Dirac mass $M_H = \pm M + \mu_S/2$. As μ_S does not play much role in any other prediction, we assume that it fits the neutrino oscillation data and one can determine it by inverting the inverse see-saw formula and using experimental results of neutrino masses and mixings.

The model achieves precision gauge coupling unification as shown in figure 1a. Symmetry breaking at TeV scale gives low mass Z' and avails a suitable platform for implementing TeV-scale inverse see-saw mechanism. The model can be testified for its predictions of observable non-unitarity effects and lepton flavour violating (LFV) decays for $\tau \to e\gamma$ (Br $\simeq 10^{-14}$), $\tau \to \mu\gamma$ (Br $\simeq 10^{-12}$) and $\mu \to e\gamma$ (Br $\simeq 10^{-16}$). We find that these contributions are very large, only 3–6 order less than the current experimental bounds [35,36], and are accessible to the ongoing or future searches. The CP-violation in non-degenerate M scenario gives $\Delta J \simeq 10^{-4}$ due to non-unitarity effects. The quark–lepton symmetric origin of the Dirac neutrino mass matrix plays a crucial role in enhancing non-unitarity, LFV and leptonic CP-violation. Another testing ground for the model could be through the $SO(10)$ prediction on gauge boson-mediated proton decay for which dedicated search experiments are going on at Super-K. The model predicts proton lifetime $\tau_{\text{pred}}(p \to e^+\pi^0) = 2 \times 10^{34\pm0.32}$ yr, which is very close to the current experimental bound $\tau_{\text{exp}}(p \to e^+\pi^0) > 1.4 \times 10^{34}$ yr [23,37].

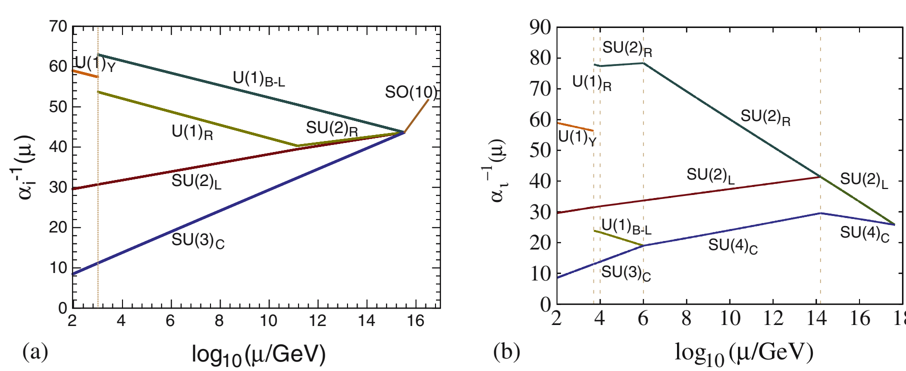

Figure 1. Two-loop gauge coupling evolution: (**a**) corresponds to breaking scheme of eq. (1) [33] and (**b**) to scheme of eq. (4) [38].

For other possibilities of TeV inverse see-saw motivated $SO(10)$ GUT, we find that the minimal single-step breaking to the TeV scale gauge symmetry $SO(10) \to G_{2113}$ is ruled out by gauge coupling unification constraints. The two-step breaking chains like $SO(10) \to G_{2_L 2_R 4_C D} \to G_{2113}$, $SO(10) \to G_{224} \to G_{2113}$, $SO(10) \to G_{2_L 1_R 4_C} \to G_{2113}$ and $SO(10) \to G_{2213D} \to G_{2113}$ with the minimal particle content are ruled out by the existing lower bound on proton lifetime. Here D stands for the D-parity preservation.

The richness of promising predictions is enhanced in the breaking schemes with $n \geq 4$ when Pati–Salam (PS) symmetries, with and without D-parity, are invoked as intermediate symmetries. Two such breaking schemes are the following [31,38,39]

$$SO(10) \xrightarrow[54_H]{10^{16.1}} G_{224D} \xrightarrow[210_H]{10^{13.45}} G_{224} \xrightarrow[210_H]{10^{6.3}} G_{2113} \xrightarrow[126_H+16_H]{10^{3.7}} \text{SM}, \tag{3}$$

$$SO(10) \xrightarrow[54_H]{10^{17.8}} G_{224D} \xrightarrow[210_H]{10^{14.2}} G_{224} \xrightarrow[210_H]{10^{6}} G_{2213} \xrightarrow[210_H]{10^{4}} G_{2113} \xrightarrow[126_H+16_H]{10^{3.7}} \text{SM}, \tag{4}$$

where all the breaking scales, inscribed atop of arrows, are in GeV. Presence of G_{224D} at high scale plays a crucial role in lowering the $W_R^{\pm}$ gauge boson mass without loosing the gauge coupling unification, as shown in figure 1b. In scheme (3), only a TeV scale Z' is detectable at LHC. The $W_R^{\pm}$ gauge boson acquires mass at G_{224} breaking scale. The gauge coupling unification figure is not provided but is similar to figure 1b. But, in sharp contrast to the scheme in (4), this scheme predicts Hyper-K [40] verifiable $|\Delta(B-L)| = 0$ proton decay $\tau(p \to e^+\pi^0) \simeq 1.05 \times 10^{35\pm1.0\pm0.35}$ yr. On the other hand, in scheme (4) TeV scale LR gauge symmetry emerges. So, $W_R^{\pm}$ are also predicted at the LHC or future collider reachable scales (figure 1b). Due to change in scheme of gauge symmetry breaking, the scalar content at different scales also change, changing the fate of gauge couplings. The extended survival hypothesis requires the unification scale to exist at very high scale in this scheme. Additional fine tuning in the masses of scalar multiplets, like $(3_L, 3_R, 1_C)$, is required to get Hyper-K reachable proton lifetime prediction. The Yukawa Lagrangian for both the schemes is

$$\begin{aligned}\mathcal{L}_{\text{Yuk}} &= Y^a 16.16.10_H^a + f16.16.126_H^{\dagger} + y_\chi 16.1.16_H^{\dagger} + \mu_S 1.1 \\ &\ni Y_\nu \bar{l}_l N\phi_u + fN^C N\Delta_R + Y_\chi \bar{N}S\chi_R + \mu_S S^T S + \text{h.c.}\end{aligned} \tag{5}$$

which introduces another element $M_N = fv_{\Delta_R}(\gg M)$ in the complete neutrino mass matrix. The light neutrino masses are still governed by inverse see-saw formula, but now the heavy neutrino masses split into light ($M_S \sim MM_N^{-1}M^T$) and heavy sectors ($M_H \sim M_N$). The representation 126_H is important because it helps in fermion mass fitting in the renormalizable theory, contributes in breaking of G_{2113} symmetry, splits the mass scales into sterile and right-handed neutrinos in contrast to pseudo-Dirac masses in inverse see-saw, thus helping in neutrinoless double beta ($0\nu\beta\beta$) decay prediction, and avails diquarks at G_{224} breaking scale mediating $n-\bar{n}$ oscillation. The representation 16_H is necessary for inverse see-saw.

D-parity restoration pushes most of the larger sized submultiplets down to the parity, restoring intermediate scale, reducing the size of GUT-threshold effects on the unification scale and proton lifetime, while the GUT-threshold effects on $\sin^2\theta_W$ or G_{224D} breaking scale have an exactly vanishing contribution [39]. The models also predict: (1) large

CP and LFV, which are of the same order as predicted in model (1) [33], (2) dominant contributions to $0\nu\beta\beta$ decay rate in $W_L^- - W_L^-$ channel through relatively light sterile neutrino exchanges, (3) experimentally reachable $n-\bar{n}$ oscillation time ($\tau_{n-\bar{n}} \sim 10^8$–$10^{11}$ s), (4) new bounds on PS symmetry breaking scale ($M_C > 1.86 \times 10^6$ GeV) from gauge-mediated rare kaon decay ($K_L \to \mu e$) etc.

In addition to non-unitarity and LFV, the Dirac neutrino mass matrix is also found to play a crucial role in enhancing $0\nu\beta\beta$ decay rate. Lower bounds on $0\nu\beta\beta$-decay lifetime coming from Heidelberg–Moscow [13], KamLAND-Zen [15], GERDA [16], EXO-200 [17] and IGEX [19] experiments constrain any new contribution to $0\nu\beta\beta$-decay, severely. In the W_L–W_L channelled sterile neutrino-mediated $0\nu\beta\beta$ decay, this constraint appears on the N–S mixing matrix M (since other matrices μ_S, M_D and M_N are fixed by the theory) which constrains physical mass of the sterile neutrino M_S. In figure 2, we have plotted lifetime vs. lightest sterile mass. Scatter plot gives the probability density of parameter space for: the allowed values of two heavier sterile masses, uncertainty in nuclear matrix elements for light and heavy neutrinos, and Majorana CP-violating phases over the full allowed parameter space. We find that the lightest sterile neutrino of mass $\sim$15$-$22 GeV is capable of explaining the possible future signature or claim of the part of Heidelberg–Moscow experiment. For hierarchical light neutrinos, sterile neutrino mass $M_{S_1} < 15$ GeV is ruled out by the present bounds. In the quasidegenerate scenario a close competition among light and sterile contributions with relatively opposite phases may interfere destructively, giving large lifetime, unreachable to current or future experiments. The sterile mass $M_{S_1} < 12$ GeV is ruled out for all scenarios.

Due to the presence of G_{224} symmetry at energy scale as low as $10^{6.2}$ GeV, all the diquark-type Higgs scalars in $(1_L, 3_R, 10_C) \subset 126$, mediating $n-\bar{n}$ oscillation, acquire the mass at this scale, thus predicting experimentally reachable $n-\bar{n}$ oscillation [20], without any serious fine tuning of the parameters. This baryon number violating process may also be the possible source of baryonic asymmetry of the Universe. Therefore, $n-\bar{n}$ oscillation search is equally crucial as proton decay search. In similar footings, there have been attempts to explain baryon asymmetry of the Universe [41], and the recent excess observed in searches for $W_R^{\pm}$ at CMS [42]. A possibility of suitable dark matter candidate in such models would bring all, but SUSY and hierarchy problem, of beyond Standard Model phenomenology under a single layout.

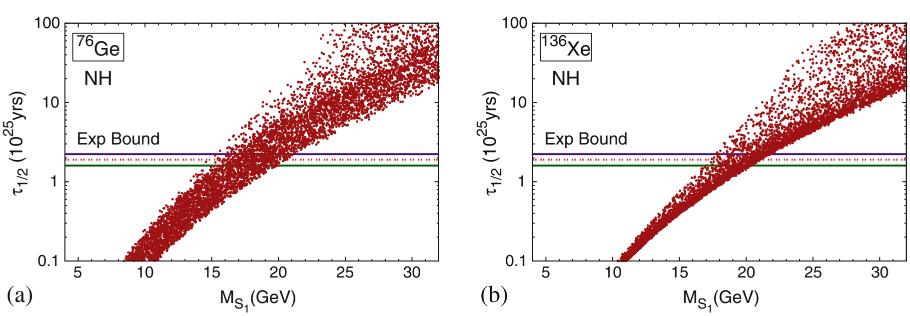

Figure 2. The $0\nu\beta\beta$ decay half-life vs. mass of the lightest sterile neutrino for two popular isotopes (**a**) ^{76}Ge and (**b**) ^{136}Xe in the normal hierarchy of light neutrinos. Scattered points for inverted hierarchy shift slightly to the left [39].

3. Summary

Multistep breaking schemes of non-SUSY $SO(10)$ gauge symmetry, with TeV scale see-saw mechanism, arise as one of the most promising grand unification framework which predicts a large number of experimentally testable phenomena. These models have verifiable predictions for several experiments which are exploring beyond SM phenomena as listed under points (c)−(i) of introduction section. A prediction for dark matter in such frameworks would make them unrivalled unification models. The SUSY GUT models are unlikely to have such a rich gauge structure at low energies and consequent predictions because the gauge couplings would meet the Landau pole before reaching the unification scale.

Acknowledgement

The author is grateful to Prof. C S Aulakh for his kind invitation in UNICOS-2014 and hospitality, and to Prof. M K Parida for collaboration and guidelines on the subject.

References

[1] Guido Altarelli, CERN-TH-98-312, 37 (July 1998), hep-ph/9809532
[2] P Langacker, *The Standard Model and beyond* (CRC Press, 2009)
[3] CMS Collaboration: S Chatrchyan *et al*, *Eur. Phys. J. C* **73**, 2568 (2013)
[4] ATL-PHYS-PUB-2013-011
[5] R Bernabei *et al*, *Int. J. Mod. Phys. A* **28**, 1330022 (2013)
[6] C E Aalseth *et al*, *Phys. Rev. D* **88**, 012002 (2013)
[7] R Agnese *et al*, *Phys. Rev. Lett.* **112**, 041302 (2014)
[8] The Fermi-LAT Collaboration: M Ackermann *et al*, *Phys. Rev. D* **89**, 042001 (2014)
[9] E Behnke *et al*, *Phys. Rev. Let.* **106**, 021303 (2011)
[10] MEG Collaboration: J Adam *et al*, *Phys. Rev. Lett.* **110(20)**, 201801 (2013)
[11] Bell Collaboration: C Schwanda *et al*, *Nucl. Phys. Proc. Suppl.* **248–250**, 67 (2014)
[12] BABAR Collaboration: Bernard Aubert *et al*, *Phys. Rev. Lett.* **104**, 021802 (2010)
[13] H V Klapdor-Kleingrothaus *et al*, *Eur. Phys. J.* **A12**, 147 (2001), hep-ph/0103062
[14] A M Bakalyarov *et al*, *Phys. Part. Nucl. Lett.* **2**, 77 (2005), arXiv:hep-ex/0309016
[15] KamLAND-Zen Collaboration: A Gando *et al*, *Phys. Rev. Lett.* **110**, 062502 (2013), arXiv:1211.3863
[16] GERDA Collaboration: M Agostini *et al*, *Phys. Rev. Lett.* **111**, 122503 (2013), arXiv:1307.4720[nucl-ex]
[17] EXO Collaboration: M Auger *et al*, *Phys. Rev. Lett.* **109**, 032505 (2012)
[18] EXO-200: J B Albert *et al*, arXiv:1402.6956
[19] IGEX Collaboration: C E Aalseth *et al*, *Phys. Rev. D* **65**, 092007 (2002), hep-ex/0202026
C E Aalseth *et al*, *Phys. Rev. D* **70**, 078302 (2004), nucl-ex/0404036
[20] M Baldo-Ceolin *et al*, *Z. Phys. C* **63**, 409 (1994)
[21] Jianming Bian, arXiv:1309.7898 (2013)
[22] T2K: Yuichi Oyama, *J. Phys. Conf. Ser.* **347**, 012005 (2012), arXiv:1108.4457
[23] Super-Kamiokande Collaboration: H Nishino, S Clark *et al*, *Phys. Rev. Lett.* **102**, 141801 (2009)
Super-Kamiokande Collaboration: C Regis *et al*, *Phys. Rev. D* **86**, 012006 (2012)
Super-Kamiokande Collaboration: H Nishino *et al*, *Phys. Rev. D* **85**, 112001 (2012)

[24] CDF Collaboration: *Phys. Rev. Lett* **107**, 191801 (2011)
[25] The BABAR Collaboration: J P Lees *et al*, arXiv:1303.6010[hep-ex]
[26] Super-Kamiokande Collaboration: K Abe *et al*, arXiv:1109.4227[hep-ex]
[27] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
[28] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
[29] R C Cotta *et al*, *New J. Phys.* **11**, 105026 (2009)
Tao Han, Zhen Liu and Aravind Natarajan, *J. High Energy Phys.* **11**, 008 (2013)
[30] K S Babu, *PoS ICHEP* **2010**, 379 (2010), arXiv:1103.3491[hep-ph]
[31] D Chang, R Mohapatra, J Gipson, R Marshak and M Parida, *Phys. Rev. D* **1718**, 31 (1985)
[32] R Mohapatra, *Phys. Rev. Lett.* **56**, 561 (1986)
[33] R L Awasthi and M K Parida, *Phys. Rev. D* **86**, 093004 (2012), arXiv:1112.1826
[34] S Antusch, J P Baumann and E Fernandez-Martinez, *Nucl. Phys. B* **810**, 369 (2009)
S Antusch, M Blennow, E Fernandez-Martinez and J Lopez-Pavon, *Phys. Rev. D* **80**, 033002 (2009)
S Antush, C Biggio, E Fernandez-Martinez, M Belen Gavela and J Lopez-Pavon, *J. High Energy Phys.* **10**, 084 (2006)
D V Forero, S Morisi, M Tartola and J W F Valle, *J. High Energy Phys.* **09**, 142 (2011)
[35] J Adam *et al*, *Phys. Rev. Lett.* **107**, 171801 (2011)
[36] K Hayasaka *et al*, *Phys. Lett. B* **666**, 16 (2008)
[37] K S Babu *et al*, arXiv:1311.5285
[38] R L Awasthi, M K Parida and S Patra, *J. High Energy Phys.* **08**, 122 (2013), arXiv:1302.0672
[39] M K Parida, R L Awasthi and P K Sahu, *J. High Energy Phys.* **01**, 045 (2015), arXiv:1401.1412
[40] K Abe *et al*, arXiv:1109.3262[hep-ex]
[41] S Patra and P Pritimita, *Eur. Phys. J. C* **74**, 3078 (2014), arXiv:1405.6836
[42] F F Deppisch, T E Gonzalo, S Patra, N Sahu and U Sarkar, *Phys. Rev. D* **90(5)**, 053014 (2014), arXiv:1407.5384[hep-ph]