A NEW SU(5) MODEL

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The standard matter-fermions and Higgses of the **27** representation of E_6 can be put in SU(5) representations in three distinct ways yielding, the Georgi–Glashow SU(5), the recently revived, and superstring related, flipped $SU(5)\times U(1)_X$ model, and a new, possibly superstring related, $SU(5)\times U(1)_X\times U(1)_\Omega$ model with unique features. The gauge symmetry is broken down to $SU(3)_C\times SU(2)_L\times U(1)_Y$ with Higgses in the $\mathbf{10}+\overline{\mathbf{10}}+\mathbf{1}+\bar{\mathbf{1}}$ representation of SU(5). The model exhibits a natural triplet–doublet splitting. Neutrinos can obtain a phenomenologically acceptable radiative Dirac mass.

While the number of compactified and four-dimensional string theories [1,2,3] is increasing, it is still difficult to single out a string theory, and a related to it gauge field theory, that has the desired phenomenological properties. In the recent superstring inspired GUT literature however, new models such as the flipped $SU(5)\times U(1)$ GUT [4,5] have appeared with unique features interesting in themselves. For example, a common property of the observable sector in field theory models that result from superstrings is the absence of any adjoint Higgses. Another feature is the appearance of extra U(1) gauge group factors [6]. These features have initiated efforts starting from the beginning and constructing new GUT models with these properties that may be obtainable from a string theory. The purpose of this article is to construct and analyze a new adjointless $N=1$ supersymmetric SU(5) model which exhibits some unique and interesting properties.

It is a common fact that the standard fermions and Higgses can be accommodated in the **27** representation of E_6 together with the right-handed neutrino, an additional pair of down-quarks and an additional singlet. Under the maximal subgroup $SO(10)\times U(1)_\Omega$ the **27** is decomposed as

$$\mathbf{27}=(\mathbf{16},1)+(\mathbf{10},-2)+(\mathbf{1},4)\,. \qquad (1)$$

Further, under the maximal subgroup $SU(5)\times U(1)_X$ of SO(10), these representations are decomposed as

$$\mathbf{27}=[(\mathbf{10},-1,1)+(\bar{\mathbf{5}},3,1)+(\mathbf{1},-5,1)] + [(\bar{\mathbf{5}},-2,-2)+(\mathbf{5},2,-2)]+[(\mathbf{1},0,4)]\,. \qquad (2)$$

In $SU(5)\times U(1)_X\times U(1)_\Omega$ there exist three distinct ways to define the hypercharge and obtain the correct assignments for the standard fermions and Higgses. The simplest case is that of the Georgi–Glashow SU(5) in which $U(1)_X\times U(1)_\Omega$ does not contribute to the hypercharge and $U(1)_Y$ is contained entirely in SU(5). The second distinct possibility is that of the "flipped" $SU(5)\times U(1)_X$ in which $U(1)_Y$ is a combination of $U(1)_X$ and a $U(1)_Z$ subgroup of SU(5). There is however a third possibility in which both $U(1)_X$ and $U(1)_\Omega$ participate in the definition of the hypercharge. In that case one gets a new $SU(5)\times U(1)_X\times U(1)_\Omega$ model quite different from the previous cases. In order to compare the differences of the three models it is worthwhile listing the field content of the matter representations in the three cases

(i) $Y=\frac{1}{6}Z$ (Georgi–Glashow SU(5)):

$$(\mathbf{10},-1,1)=\begin{pmatrix} Q \\ U^cE^c\end{pmatrix},\quad (\bar{\mathbf{5}},3,1)=\begin{pmatrix} D^c \\ L\end{pmatrix},$$

$$(\mathbf{1},-5,1)=N^c\quad (\bar{\mathbf{5}},-2,-2)=\begin{pmatrix} B^c \\ H\end{pmatrix},$$

$$(\mathbf{5},2,-2)=\begin{pmatrix} B \\ H^c\end{pmatrix},\quad (\mathbf{1},0,4)=N\,. \qquad (3)$$

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(ii) $Y=-\frac{1}{5}X-\frac{1}{30}Z$ (flipped SU(5)):

$$(\mathbf{10},-1,1)=\begin{pmatrix}\mathrm{Q}\\ \mathrm{D^cN^c}\end{pmatrix},\quad (\bar{\mathbf{5}},3,1)=\begin{pmatrix}\mathrm{U^c}\\ \mathrm{L}\end{pmatrix},$$

$$(\mathbf{1},-5,1)=\mathrm{E^c},\quad (\bar{\mathbf{5}},-2,-2)=\begin{pmatrix}\mathrm{B^c}\\ \mathrm{H^c}\end{pmatrix},$$

$$(\mathbf{5},2,-2)=\begin{pmatrix}\mathrm{B}\\ \mathrm{H}\end{pmatrix},\quad (\mathbf{1},0,4)=\mathrm{N}. \tag{4}$$

(iii) $Y=\frac{1}{4}\Omega+\frac{1}{20}X-\frac{1}{30}Z$ (doubly-flipped SU(5)):

$$\mathscr{Q}(\mathbf{10},-1,1)=\begin{pmatrix}\mathrm{Q}\\ \mathrm{B^cN}\end{pmatrix},\quad \mathscr{D}^c(\bar{\mathbf{5}},3,1)=\begin{pmatrix}\mathrm{D^c}\\ \mathrm{H^c}\end{pmatrix},$$

$$\mathscr{N}^c(\mathbf{1},-5,1)=\mathrm{N^c},\quad \mathscr{U}^c(\bar{\mathbf{5}},-2,-2)=\begin{pmatrix}\mathrm{U^c}\\ \mathrm{H}\end{pmatrix},$$

$$\mathscr{L}(\mathbf{5},2,-2)=\begin{pmatrix}\mathrm{B}\\ \mathrm{L}\end{pmatrix},\quad \mathscr{E}^c(\mathbf{1},0,4)=\mathrm{E^c}. \tag{5}$$

We have denoted with Z the U(1) generator belonging to SU(5). The quantum number assignments of the eleven Q, $\mathrm{B^c}$... fields are listed in table 1.

It is evident that the $\mathrm{SU(5)\times U(1)_X\times U(1)_\Omega}$ model is distinct from flipped SU(5) since the $\mathrm{SU(3)_C\times SU(2)_L\times U(1)_Y}$ content of 5's is different. The allowed flippings $\mathrm{B^c\leftrightarrow D^c}$, $\mathrm{L\leftrightarrow H}$, $\mathrm{N\leftrightarrow N^c}$ do not alter the fact that colour triplets of charge $\frac{1}{3}$ are together with hypercharge $+\frac{1}{2}$ isodoublets. The model is characterized by some unique features.

(i) Left-handed leptons and right-handed up-quarks belong to the **10** representation of SO(10).

(ii) The right-handed electron is an SO(10) singlet.

(iii) Left-handed quarks, right-handed down-quarks and right-handed neutrinos belong to the **16** representation of SO(10) as usually.

(iv) Higgs isodoublets of hypercharge $+\frac{1}{2}$ belong to the **16** representation while those of hypercharge $-\frac{1}{2}$ belong to the **10** representation.

The superfield content of a supersymmetric $\mathrm{SU(5)\times U(1)_X\times U(1)_\Omega}$ GUT except the gauge vector supermultiplet includes N_F chiral matter superfields $\mathscr{Q}$, $\mathscr{D}^c$, $\mathscr{N}^c$, $\mathscr{U}^c$, $\mathscr{L}$, $\mathscr{E}^c$ with the quantum number assignments shown in (5). These are exactly the building blocks of N_F copies of the **27** representation of $\mathrm{E_6}$. In addition we introduce two pairs of *massless* Higgs chiral superfields in the $(\mathbf{10},-1,1)+(\overline{\mathbf{10}},1,-1)$ and in the $(\mathbf{1},-5,1)+(\bar{\mathbf{1}},5,-1)$ representations

$$\mathscr{Q}_\mathrm{H}(\mathbf{10},-1,1)+\bar{\mathscr{Q}}_\mathrm{H}(\overline{\mathbf{10}},1,-1)$$

$$=\begin{pmatrix}\mathrm{Q_H}\\ \mathrm{B^c_H N_H}\end{pmatrix}+\begin{pmatrix}\overline{\mathrm{Q_H}}\\ \overline{\mathrm{B^c_H N_H}}\end{pmatrix},$$

$$\mathscr{N}^c_\mathrm{H}(\mathbf{1},-5,1)+\overline{\mathscr{N}^c_\mathrm{H}}(\mathbf{1},5,-1)=\mathrm{N^c_H}+\overline{\mathrm{N^c_H}}, \tag{6}$$

whose expectation value in the D-flat direction $\langle \mathrm{N_H}\rangle=\langle\bar{\mathrm{N}}_\mathrm{H}\rangle$, $\langle\mathrm{N^c_H}\rangle=\langle\bar{\mathrm{N}}^c_\mathrm{H}\rangle$ breaks $\mathrm{SU(5)\times U(1)_X\times U(1)_\Omega}$ to $\mathrm{SU(3)_C\times SU(2)_L\times U(1)_Y}$ [#1]. $\mathrm{Q_H}$,

[#1] The absense of the vacuum expectation value $\langle\mathrm{N^c_H}\rangle=\langle\bar{\mathrm{N}}^c_\mathrm{H}\rangle$ would result in an $\mathrm{SU(3)_C\times SU(2)_L\times U(1)_Y\times U(1)_{Y''}}$ model, characterized by an additional light neutral gauge boson.

Table 1
U(1) quantum numbers of matter particles in SU(5) models.

$\mathrm{SU(3)_C\times SU(2)_L\times U(1)_Y}$	SU(5)			$\mathrm{SU(5)\times U(1)_X}$			$\mathrm{SU(5)\times U(1)_X\times U(1)_\Omega}$		
	Z	X	Ω	Z	X	Ω	Z	X	Ω
$\mathrm{Q}(\mathbf{3},\mathbf{2},\frac{1}{6})$	1	−1	1	1	−1	1	1	−1	1
$\mathrm{D^c}(\bar{\mathbf{3}},\mathbf{1},\frac{1}{3})$	2	3	1	−4	−1	1	2	3	1
$\mathrm{U^c}(\bar{\mathbf{3}},\mathbf{1},-\frac{2}{3})$	−4	−1	1	2	3	1	2	−2	−2
$\mathrm{L}(\mathbf{1},\mathbf{2},-\frac{1}{2})$	−3	3	1	−3	3	1	3	2	−2
$\mathrm{E^c}(\mathbf{1},\mathbf{1},1)$	6	−1	1	0	−5	1	0	0	4
$\mathrm{N^c}(\mathbf{1},\mathbf{1},0)$	0	−5	1	6	−1	1	0	−5	1
$\mathrm{H}(\mathbf{1},\mathbf{2},-\frac{1}{2})$	−3	−2	−2	3	2	−2	−3	−2	−2
$\mathrm{H^c}(\mathbf{1},\mathbf{2},\frac{1}{2})$	3	2	−2	−3	−2	−2	−3	3	1
$\mathrm{B}(\mathbf{3},\mathbf{1},-\frac{1}{3})$	−2	2	−2	−2	2	−2	−2	2	−2
$\mathrm{B^c}(\bar{\mathbf{3}},\mathbf{1},\frac{1}{3})$	2	−2	−2	2	−2	−2	−4	−1	1
$\mathrm{N}(\mathbf{1},\mathbf{1},0)$	0	0	4	0	0	4	6	−1	1

$\bar{Q}_H$ and two singlets, linear combinations of N_H, $\bar{N}_H$, N^c_H and $\bar{N}^c_H$, are absorbed while B^c_H and $\bar{B}^c_H$ and two other combinations of singlets are left-over.

Consider now the cubic superpotential [#2]

$$W_0 = g_{ijk}(u, d)\mathcal{Q}_i \mathcal{D}^c_j \mathcal{U}^c_k + g_{ijk}(v)\mathcal{L}_i \mathcal{D}^c_j \mathcal{N}^c_k + g_{ijk}(e)\mathcal{L}_i \mathcal{U}^c_j \mathcal{E}^c_k + g_{ij}(H)\mathcal{Q}_i \mathcal{Q}_H \mathcal{L}_j \quad (7)$$

The first term of (7)

$$g(u, d)(QD^cH + QU^cH^c + B^cD^cU^c + NHH^c) \quad (8)$$

is responsible for up-and down-quark masses. The fact that both up-and down-quark masses result from a common coupling is a unique feature of this model not shared by the other SU(5) models.

The second term of the superpotential (7)

$$g(v)(LN^cH^c + D^cN^cB) \quad (9)$$

is responsible for the neutrino Dirac mass. The fact that the Yukawa coupling responsible for the neutrino Dirac mass is independent from the other Yukawa couplings makes it technically possible, although not neccessarily appealing, to have Dirac neutrinos light as required by phenomenology by adjusting $g(v)$ to a small value. We shall come back later to the problem of the neutrino mass and shown how it can be naturally solved through a modification of the model.

The third term in (7)

$$g(e)(LHE^c + BU^cE^c) \quad (10)$$

is responsible for charged lepton masses.

Finally, the last term

$$g(H)(QQ_HB + QB^c_HL + B^cQ_HL + B^cN_HB + NB^c_HB) \quad (11)$$

leads to a superheavy mass for the B and B^c fields

$$g_{ij}(H)\langle N_H \rangle B^c_i B_j . \quad (12)$$

Thus all baryon number violating couplings present in (8), (9) and (10) become harmless due to the supermassiveness of B and B^c. Apart from the not very crucial terms $\mathcal{Q}\mathcal{Q}\mathcal{L}$ and $\mathcal{Q}_H\mathcal{Q}_H\mathcal{L}$, the discrete symmetry imposed forbids a dangerous term $\mathcal{Q}_H\mathcal{D}^c\mathcal{U}^c$ which contains a superheavy mass $\langle N_H \rangle H_i H^c_j$ for the Higgs isodoublets. This term would spoil the lightness of the Higgs isodoublets. It is also the main obstacle to a straightforward extention of the present model to an $SO(10)\times U(1)_\Omega$ GUT.

The model as it stands, below $\langle N_H \rangle = \langle \bar{N}_H \rangle \approx \langle N^c_H \rangle = \langle \bar{N}^c_H \rangle \simeq M_X$ contains N_F quarks and leptons as well as N_F pairs of Higgs isodoublets. In addition, except the two Higgs singlets, it contains N_F massless singlets N_i and one pair of massless colour triplets B^c_H and $\bar{B}^c_H$. Masses for this additional set of fields would be absent even when supersymmetry is broken unless we consider new interactions. These could arise either from a gauge singlet sector or a massive Higgs sector. The model can be extended to include N_F *massive* gauge singlet superfields $\mathbf{\Phi}_i(1, 0, 0)$ and two pairs of *massive* superfields [#3]

$$\mathcal{D}^c_H(\bar{5}, 3, 1) + \overline{\mathcal{D}^c_H}(5, -3, -1) + \mathcal{U}^c_H(\bar{5}, -2, -2) + \overline{\mathcal{U}^c_H}(5, 2, 2)$$

The superpotential now will include the terms [#4]

$$W_1 = f_{ij}\mathcal{Q}_i \overline{\mathcal{Q}_H}\mathbf{\Phi}_j + \lambda_i \mathcal{Q}_H \mathcal{D}^c_H \mathcal{U}^c_i + \lambda \overline{\mathcal{Q}_H}\,\overline{\mathcal{D}^c_H}\,\overline{\mathcal{U}^c_H} + \lambda'_i \mathcal{Q}_H \mathcal{D}^c_i \mathcal{U}^c_H + \lambda''_i \mathcal{Q}_i \mathcal{D}^c_H \mathcal{U}^c_H + g_i \mathbf{\Phi}_i \mathcal{D}^c_H \overline{\mathcal{D}^c_H} + g'_i \mathbf{\Phi}_i \mathcal{U}^c_H \overline{\mathcal{U}^c_H} + f_{ijk}\mathbf{\Phi}_i\mathbf{\Phi}_j\mathbf{\Phi}_k + M_{ij}\mathbf{\Phi}_i\mathbf{\Phi}_j + M(\mathcal{D}^c_H \overline{\mathcal{D}^c_H} + \mathcal{U}^c_H \overline{\mathcal{U}^c_H}) . \quad (13)$$

The first term in (13)

$$f(B^c\bar{B}^c_H\Phi + Q\bar{Q}_H\Phi + N\bar{N}_H\Phi) \quad (14)$$

provides us with a Dirac mass term $f_{ij}\langle \bar{N}_H \rangle N_i \mathbf{\Phi}_j$ which combines with the term $M_{ij}\mathbf{\Phi}_i\mathbf{\Phi}_j$ and gives masses of order M^2_X/M for N_i [#5].

Another important function of the same coupling is that it can generate through radiative corrections masses for the B^c_H and $\bar{B}^c_H$ fields as shown in fig. 1. A lower mass limit on this mass is imposed from the, in general, family changing coupling $Q_iL_jB^c_H$ that can induce operators bvūē, τ̄ēuū, etc. with interesting phenomenological signatures.

[#2] This is the most general under the discrete $Z_2\times Z_2$ symmetry $\mathcal{Q}_H$, $\mathcal{Q}$, $\mathcal{U}^c$, $\mathcal{L}$, $\mathcal{N}^c \to -\mathcal{Q}_H$, $-\mathcal{Q}$, $-\mathcal{U}^c$, $-\mathcal{L}$, $-\mathcal{N}^c$, $\mathcal{N}^c_H \to -\mathcal{N}^c_H$.

[#3] Note that all fields belong to complete or incomplete 27 and $\overline{27}$ resp. of E_6.

[#4] The trilinear part is the most general under the extension of the first Z_2 discrete symmetry $\mathcal{D}^c_H$, $\overline{\mathcal{D}^c_H} \to -\mathcal{D}^c_H$, $-\overline{\mathcal{D}^c_H}$.

[#5] It is natural to assume that M, M_{ij} are of the order of the Planck mass i.e. $O(10^{18}$ GeV). Similarly, couplings to extra singlets χ, $\mathcal{Q}_H\bar{\mathcal{Q}}_H\chi + \mathcal{N}^c_H\overline{\mathcal{N}^c_H}\chi$ can render the surviving Higgs singlets in $\mathcal{Q}_H$, $\bar{\mathcal{Q}}_H$, $\mathcal{N}^c_H$ and $\overline{\mathcal{N}^c_H}$, massive.

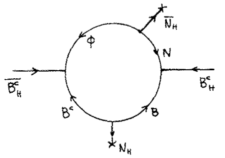

Fig. 1. Radiative mass of B^c_H and $\bar{B}^c_H$.

The other terms in (13), apart from the irrelevant $B^c_H D^c_H U^c$, $B^c_H D^c U^c_H$, $\bar{B}^c_H \bar{D}^c_H \bar{U}^c_H$, $QD^c_H H_H$, ... etc, include

$$\lambda_i \langle N_H \rangle H_i H^c_H + \lambda'_i \langle N_H \rangle H^c_i H_H$$
$$+ \bar{\lambda} \langle \bar{N}_H \rangle \bar{H}^c_H \bar{H}_H + M(H^c_H \bar{H}^c_H + H_H \bar{H}_H) . \quad (15)$$

Thus, one combination, namely $\lambda_i H_i$ and $\lambda'_i H^c_i$, of Higgs isodoublets become massive of an intermediate mass. This is evident from the Higgs isodoublet mass matrix which is (roughly)

$$\begin{pmatrix} 0 & M'_X & 0 \\ M_X & 0 & M \\ 0 & M & M''_X \end{pmatrix} \quad (16)$$

in a $\lambda_i H_i$, H_H, $\bar{H}^c_H$ and $\lambda'_i H^c_i$, H^c_H $\bar{H}_H$ basis. The eigenvalues of the mass matrix (16) are approximately

$$M, -M, O(M^3_X/M^2) . \quad (17)$$

It is important that the introduced couplings to the massive Higgses make one combination of Higgs isodoublets heavy. To many light Higgs isodoublets destroy the predicted value of the electroweak mixing angle.

As we mentioned previously, neutrinos can obtain a direct Dirac mass from the coupling $g(v)LH^cN^c$ which is unrelated to any other Yukawa coupling and therefore it would be technically possible to adjust it to a phenomenologically acceptable value. Nevertheless this is not theoretically satisfactory. It is possible to have the standard neutrino mass term $\mathscr{L}\mathscr{D}^c\mathscr{N}^c$ forbidden, and therefore the direct neutrino mass term absent, due to the properties of $\mathscr{N}^c$ under the imposed discrete symmetry. Thus, if we had $\mathscr{N}^c \to \mathscr{N}^c$, $\overline{\mathscr{N}^c_H} \to -\overline{\mathscr{N}^c_H}$, under Z_2, no tree-level neutrino mass is present. However, the neutrino field would still be able to couple to $\mathscr{L}$ through the, now allowed, term $\mathscr{L}\mathscr{D}^c_H\mathscr{N}^c = LH^c_H N^c + BD^c_H N^c$. No vacuum expectation value for H^c_H is possible since it is superheavy and consequently still no tree-level mass for the neutrino is present. Nevertheless, radiative corrections through the diagrams shown in fig. 2 generate a naturally small neutrino Dirac mass in agreement with phenomenology [7].

The model as it stands now contains N_F light families of quarks and leptons, and pair of light B^c_H and $\bar{B}^c_H$, $(N_F - 1)$ pairs of light Higgs isodoublets and one pair of intermediate-mass Higgs isodoublets. The rest of the fields are massive below M_X. The renormalization group analysis of the model gives $\sin^2\theta_W$ in agreement with current experimental values for a range of values of the parameter

$$\tilde{\alpha} = [\tfrac{3}{20}\alpha^{-1}_{\tilde{X}}(M_X) + \tfrac{9}{4}\alpha^{-1}_{\tilde{\Omega}}(M_X)]^{-1} , \quad (18)$$

where $\alpha_{\tilde{X}}$ and $\alpha_{\tilde{\Omega}}$ are the couplings of the normalized [#6] $U(1)_X$ and $U(1)_\Omega$. The values obtained for $N_F = 3$ are shown in table 2 [#7]. Most of the favorable values for the mixing angle however occur for α values for which $\alpha_{\tilde{\Omega}}(M_X) > \alpha_5(M_X)$ and "E_6 unification" is excluded. $SO(10) \times U(1)_\Omega$ unification is possible for specific choices of $\alpha_{\tilde{X}}$ and $\alpha_{\tilde{\Omega}}$. It all depends of course on the particle content above M_X.

Summarizing, we have proposed and analysed an

[#6] We introduce the normalized (for the **27** representation of E_6) U(1) generators $\tilde{Z} = (\sqrt{\frac{1}{90}})Z$, $\tilde{X} = (\sqrt{\frac{1}{60}})X$, $\tilde{\Omega} = \frac{1}{6}\Omega$ (Tr $\tilde{Z}^2$ = Tr $\tilde{X}^2$ = Tr $\tilde{\Omega}^2 = 2$) and consequently $\alpha_{\tilde{X}} = \frac{1}{60}\alpha_X$, $\alpha_\Omega = \frac{1}{36}\alpha_{\tilde{\Omega}}$, $\alpha_Z = \frac{1}{90}\alpha_{\tilde{Z}}$ and $Y = \frac{3}{2}\tilde{\Omega} + \sqrt{\frac{3}{20}}\tilde{X} - \sqrt{\frac{1}{10}}\tilde{Z}$. Then, according to ref. [8] $1/\alpha_Y = \frac{9}{4}/\alpha_{\tilde{\Omega}} + \frac{3}{20}/\alpha_{\tilde{X}} + \frac{1}{10}\alpha_{\tilde{Z}} = 1/\tilde{\alpha} + \frac{1}{10}/\alpha_{\tilde{Z}}$

[#7] We have used $\alpha_s = 0.13$, $\alpha = 1/128$. We have assumed that $M = 10^{18}$ GeV and that the mass of the intermediate scale isodoublet pair is M^3_X/M^2 in accordance with (17).

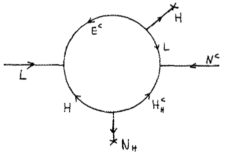

Fig. 2. Radiative neutrino mass.

Table 2
Values for the $\sin^2\theta_W(M_W)$, M_X and $\alpha_5(M_X)$.

$\tilde{\alpha}^{-1}$	$\sin^2\theta_W$	M_X (GeV)	α_5
26	0.237	7.30×10^{16}	5.38×10^{-2}
28	0.234	2.75×10^{16}	5.47×10^{-2}
30	0.232	1.04×10^{16}	5.57×10^{-2}
32	0.230	3.90×10^{15}	5.56×10^{-2}
34	0.227	1.47×10^{15}	5.77×10^{-2}
36	0.225	5.53×10^{14}	5.87×10^{-2}
38	0.222	2.08×10^{14}	5.98×10^{-2}

adjointless $SU(5)\times U(1)_X\times U(1)_\Omega$ model which may be obtainable from a string theory and which exhibits a set of attractive properties. It has a natural triplet doublet mass splitting, it leads to phenomenologically acceptable values for $\sin^2\theta_W$ and it predicts naturally light neutrinos.

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