The see-saw mechanism in string models

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The neutrino mass problem is discussed in the context of the E_6, SU(5)×U(1) and SU(4)×SO(4) models. It is found that the right handed neutrinos receive large Majorana masses radiatively, through a two loop diagram originally proposed by Witten for the SO(10) theory. Thus an effective see-saw mechanism becomes effective. The resulting left handed neutrino mass spectrum is discussed in detail in each model separately.

1. Introduction

In this letter we are going to show that by utilizing the Witten mechanism [1], it is possible to provide a nice explanation of the neutrino mass problem in the viable models E_6 [2], flipped SU(5) [3] and SU(4)×O(4) [4,5].

As is well known, in any gauge theory one must specify the underlying symmetry and its particle content. Thus there exists an arbitrariness in the particle content of the theory and in particular in the Higgs sector, which has been exploited to accommodate the various stages of the symmetry breaking. Invariably additional Higgs representations were needed to provide an explanation of the observed fermion spectrum and in particular the small neutrino mass. An attempt to limit this proliferation of Higgs particles was provided by Witten [1]. His proposal was however pretty much ignored in the construction of GUT models which aimed to explain the neutrino mass at the tree level. It was therefore forgotten later on even though the prevailing string theories imposed stringent constraints on the admissible Higgs representations and the incorportation of the Witten mechanism could only help the string models solve their problems in the neutrino sector.

The question of neutrino mass is one of the most intriguing issues in particle physics [#1]. In the context of the standard model the neutrinos are massless, since there is no Dirac mass due to the absence of the right handed neutrino. The Majorana mass is also absent since lepton number is conserved in the standard model (the lepton number violation due to the anomaly is negligible). In the SU(5) model the neutrinos remain massless since still there is no room for the right handed neutrino in the $\underline{10}+\underline{\bar{5}}$ matter representations which accommodate the 15 known fermions of each generation. The exact $B-L$ conservation prevents the presence of Majorana masses. The situation remains the same if one introduces SU(5) singlets of right handed neutrinos (we will see later that the Witten mechanism is not effective in this case).

2. The Witten mechanism in the GUT SO(10) model

In the GUT SO(10) model there is room for the right handed neutrino in the spinorial $\underline{16}$ dimensional representation. In this minimal version of the model however the neutrino Dirac mass is naturally equal to the up quark mass of the same generation and thus in conflict with the experiment. One thus is forced to introduce the $\underline{126}$ dimensional representation of SO(10) to generate a Majorana mass at the tree level. By giving a VEV to the isotriplet and isosinglet members of this representation one can generate a neutrino mass matrix which for one generation takes the form

[#1] For a review see ref. [6].

$$(\nu \quad \nu^c)\begin{pmatrix} m & m_u \\ m_u & M \end{pmatrix}\begin{pmatrix} \nu \\ \nu^c \end{pmatrix}. \tag{1}$$

If the isotriplet of Higgs does not acquire a VEV, which is the most favorable scenario, then $m=0$. Now the left handed neutrino remains light provided that M is sufficiently large. One finds

$$m_\nu = m_u^2/M, \quad M_{\nu^c} = M, \tag{2}$$

thus for $m_u = 10$ MeV and $M = M_{GUT} = 10^{14}$ GeV one gets $m_\nu = 10^{-9}$ eV. More quantitative calculations in the context of the SO(10) model [7] yield a neutrino spectrum consistent with experiments. Admittedly, however, there is a lot of arbitrariness in the couplings of the $\underline{126}$ with its many other useless particles.

A more economic mechanism for generating the large scale mass which does not require the introduction of the $\underline{126}$ was proposed by Witten [1]. It is only necessary to go to the two loop level (see fig. 1). The neutrino Majorana mass is given by

$$M^{\rm rad}_{\nu^c} = 10^7 m_u, \tag{3}$$

which leads to

$$m_{\nu_1} = 0.5 \text{ eV}, \quad m_{\nu_2} = 150 \text{ eV}, \quad m_{\nu_3} = 10 \text{ keV}, \tag{4}$$

which are consistent with the present experimental bounds but their sum violates the cosmological bound ($\sum m_{\nu_i} < 50$ eV).

The Witten mechanism is not operative in the traditional SU(5) model since ν^c is not contained in any nontrivial representation of the gauge group, so we will go directly to some more interesting models. We will begin with the E_6 model which is encountered in the heterotic $E_8 \times E_8$ string theory.

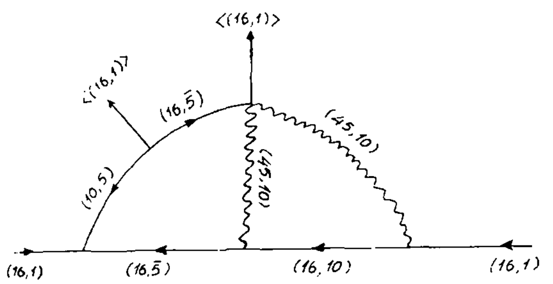

Fig. 1. Two loop diagram that gives mass to ν^c in the SO(10) theory.

3. The E_6 model

In the case of the ten dimensional heterotic string theory one ends up after compactification with a field theory in four dimensions which is characterized by the observable gauge group E_6. The chiral fields belong to the 27 of E_6 which under SO(10) decomposes as follows:

$$\underline{27} \to (Q, l, d^c, e^c, \nu^c) + (D, H, D^c, \bar{H}) + \eta. \tag{5}$$

The gauge bosons belong to the adjoint $\underline{78}$ dimensional representation which under SO(10) decomposes as follows:

$$\underline{78} \to \underline{45} + \underline{16} + \overline{\underline{16}} + 1, \tag{6}$$

where $\underline{45}$ is the adjoint representation of SO(10). The neutrino mass matrix for each generation is a 5×5 matrix consisting of the fields (ν_L, N_L, N^c_L, ν^c_L, n_L), where N_L and N^c_L are the neutral members of H and $\bar{H}$. This matrix has been analyzed previously [2]. One needs a Majorana mass matrix m_M in the (ν^c_L, n_L) subspace which can be obtained only via nonrenormalizable terms. Then, the see-saw mechanism becomes effective if

$$(\det m_M)^{1/2} > 10^4 \text{ GeV}. \tag{7}$$

There is no need of nonrenormalizable terms in the present approach since the above Majorana submatrix can be generated via the Witten mechanism as shown in figs. 2a, 2b. In order to be able to construct the two loop diagrams of these figures we need a $\underline{27}$ Higgs representation which we will denote with $\underline{27'}$ to distinguish it from the $\underline{27}$s for the fermion families. This Higgs develops VEVs along the components ν^c_H in fig. 2a and η^c_H in fig. 2b. In order to evaluate the two loop integral of figs. 2a and 2b we make the following assumptions: (i) The mass of the virtual fermions of ($\underline{27}$, $\underline{16}$) and of the colorless gauge boson is zero. (ii) The masses of the other internal particles are equal to $M = M_{GUT}$. Then we find that the isosinglet Majorana mass of fig. 2a is given by

$$M'_1 = M_{\nu\nu^c} = \varepsilon\left(\frac{\alpha}{4\pi}\right)^2 \frac{m_q}{m_W} A\left(\frac{\langle \nu^c_H \rangle^2}{M}\right), \tag{8}$$

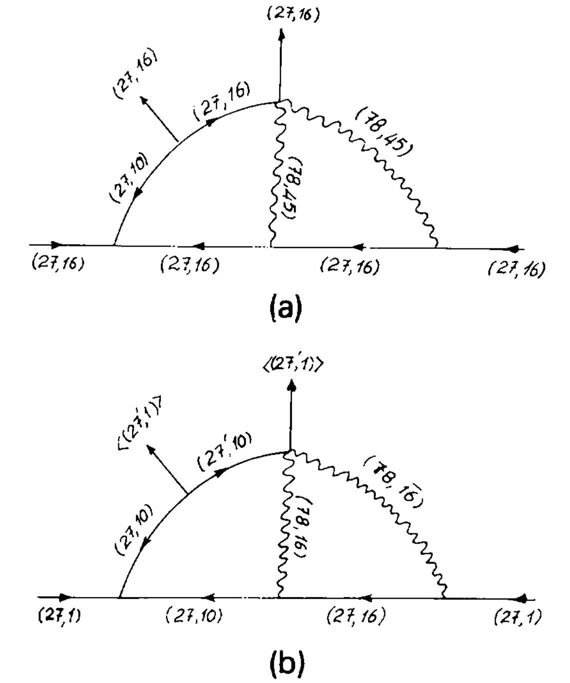

Fig. 2. (a) Two loop diagram in the E_6 that gives mass to ν^c. (b) Two loop diagram in the E_6 that gives mass to the singlet η.

where ε is the mixing between the (27, $\underline{16}$) and (27, 10), m_q/m_W is the coupling ($\underline{27}$, $\underline{16}$)($\underline{27}$, $\underline{16}$), ($\underline{27}$, $\underline{10}$) and arises in a way analogous to that of Witten's case. The quantity A results from the loop calculations and is found to be

$$A=\int_0^1 (1-x)\,dx \times \int_0^x dy \int_0^1 dw \int_0^w z\,dz \frac{1}{xz(1-x)+(1-w)y} = \tfrac{3}{16}\,.$$

For fig. 2b the mass is calculated analogously and is found to be

$$M'_2=M_{\eta\eta^c}=\left(\frac{\alpha}{4\pi}\right)^2 \frac{3}{16}\left(\frac{m_q}{m_W}\right)\left(\frac{\langle\eta^c_H\rangle^2}{M}\right). \qquad (9)$$

We take $\alpha=0.04$, which is a bit more optimistic than the apparent choice of Witten ($\alpha=0.01$). Assuming further that $\nu^c_H \approx M=10^{16}$ GeV (SO(10) breaking scale) and $\varepsilon=10^{-1}$ we get

$$M_{\nu\nu^c}=2.5\times10^7 m_q\,. \qquad (10)$$

The Majorana mass involving the η_L is heavier since $\langle\eta^c_H\rangle$ is associated with the E_6 breaking scale. Taking $\langle\eta^c_H\rangle\approx M=10^{17}$ GeV we get

$$M_{\eta\eta^c}=2.5\times10^9 m_q\,, \qquad (11)$$

$$D=(\det m_M)^{1/2}=2.5\times10^8 m_q\,. \qquad (12)$$

Taking $m_q=10$ MeV we get $D=0.85\times10^7$ GeV. Since we do not know the precise form of neutrino generation mixing, i.e. the full 15×15 neutral fermion mass matrix, we will ignore generation mixing. Then the see-saw mechanism yields

$$m_\nu=\xi m_q^2/M=\xi\times0.4\times10^{-8} m_q\,. \qquad (13)$$

The parameter ξ depends on the details of the mass matrix but in the present treatment is of order one. Thus we get

$$m_{\nu_1}=2\times10^{-2}\,\text{eV},\quad m_{\nu_2}=6\,\text{eV},\quad m_{\nu_3}=0.4\,\text{keV}\,, \qquad (14)$$

which are consistent with the experimental bounds but as in Witten's case, the sum exceeds the cosmological bound.

4. The flipped SU(5) model

In the case of the SU(5)×U(1) model the right handed neutrino is no longer an SU(5) singlet but a member of the $\underline{10}$ dimensional representation. With the collaborative effort of the SU(5) gauge bosons, which are members of the adjoint $\underline{24}$ dimensional representation, and the Higgs fields $H=\underline{10}$, $\bar{H}=\overline{\underline{10}}$, and $h=\underline{5}$, one can get an isosinglet neutrino Majorana mass term at the two loop level as indicated in fig. 3. Note that the gauge boson attached to the isosinglet neutrino must be colored. The needed Yukawa couplings are [3] $\lambda_1^{ij}F_iF_jh+\lambda_3 HHh$. The first term can be decomposed as follows:

$$\lambda_1^{ij}F_iF_jh=\lambda_1^{ij}(\langle h\rangle d_i d_j^c+\nu_i^c d_j^c D_h)$$
$$=m_d d_i d_j^c+(m_d/m_W)\nu_i^c d_j^c D\,. \qquad (15)$$

One then obtains from fig. 3 the following isosinglet Majorana mass:

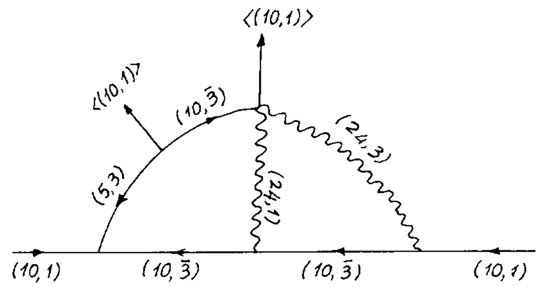

Fig. 3. Two loop diagram in the SU(5)×U(1) that gives mass to ν^c.

$$M_{\nu\nu^c} \approx \left(\frac{\alpha}{4\pi}\right)^2 \frac{3}{16}\left(\frac{m_d}{m_W}\right) M_{\rm GUT} \,. \tag{16}$$

The above expression was obtained assuming that $\lambda_3\langle H\rangle \approx \varepsilon\langle H\rangle \approx M_{\rm GUT}$, where ε is the mixing between D_h and d^c_H. For $M_{\rm GUT}=10^{16}$ GeV and $\alpha=0.056$ [8] we obtain

$$M_{\nu\nu^c} = M^{\rm rad} \approx 4.7\times 10^8 m_d \,, \tag{17}$$

i.e. the isosinglet Majorana neutrino mass is proportional to the down quark mass. Neglecting the mixing between different generations the see-saw mechanism yields

$$m_{\nu_1} = 5.3\times 10^{-3}\ {\rm eV}, \quad m_{\nu_2} = 30\ {\rm eV}, \quad m_{\nu_3} = 4.1\ {\rm keV}\,. \tag{18}$$

Thus in the flipped SU(5) the standard see-saw mechanism is not effective in yielding a light tau-neutrino mass such as to respect the cosmological bound, since the isosinglet heavy Majorana mass is proportional to the m_d mass and not to m_u. It is possible however to extend the see-saw mechanism by introducing new couplings with extra singlet fields [3] which suppress further the light neutrino masses (see also the discussion in section 6). In the string version of the model, the violation of the cosmological bound can be avoided naturally. In fact one can find the following trilinear couplings [9] for the tau neutrino:

$$g\sqrt{2}\,(\langle N^c_5\rangle \nu^c_\tau \Phi_3 + \langle \bar{h}_{45}\rangle \nu^c_\tau \nu_\tau) \,, \tag{19}$$

where Φ_3 is a neutral singlet field which couples to the right handed tau neutrino. Setting $g\sqrt{2}\,\langle h_{45}\rangle = m_t$ and $g\sqrt{2}\,\langle N^c_5\rangle = M$, and assuming a Majorana type mass μ for Φ_3 which might arise from a higher order non renormalizable term, we obtain the following mass matrix:

$$(\nu \quad \nu^c_\tau \quad \Phi_3)\begin{pmatrix} 0 & m_t & 0 \\ m_t & M^{\rm rad.} & M \\ 0 & M & \mu \end{pmatrix}\begin{pmatrix} \nu \\ \nu^c_\tau \\ \Phi_3 \end{pmatrix} . \tag{20}$$

Thus the left handed tau neutrino will get a mass $m_{\nu_3} = m_t^2\mu/M^2 < 10^{-3}$ eV, thus within the cosmological bounds.

6. The SU(4)×O(4) model

From the point of view of Witten's mechanism, this is perhaps the most interesting model. Its main advantage is that the Yukawa coupling which is involved in the calculation of the Majorana neutrino mass from the two loop diagram analogous to that of figs. 1–3, is not longer related to the up or down quark mass. Thus in principle this coupling could be as large as of order one. The resulting neutrino masses for ν^c turn out to be bigger than in the previous cases and the see-saw mechanism is operative for the neutrinos of all families. In order to see this let us first write down all the possible trilinear Yukawa couplings of this model. They are [4]

$$\begin{aligned} W = {} & \lambda_1 F_{Li}\bar{F}_{Rj} h + \lambda_2 \bar{F}_R H \Phi_i + \lambda_3 HHD \\ & + \lambda_4 \bar{H}\bar{H}D + \lambda_5 hh\Phi_i + \lambda_6 \Phi_i\Phi_j\Phi_k \\ & + \lambda_7 F_{Li}F_{Li}D + \lambda g\bar{F}_{Rj}\bar{F}_{Rj}D + \lambda_9 DD\Phi_i \,, \end{aligned} \tag{21}$$

where $F_L + \bar{F}_R = (4, 2, 1) + (\bar{4}, 1, 2)$ are the 16 fermion fields of each generation, $h(1, 2, 2) = h(1, 2, -1) + h^c(1, 2, 1)$ are the electroweak doublets, $H(4, 1, 2)$, $\bar{H}(\bar{4}, 1, 2)$ are the Higgses needed to break the $SU(4)\times SU(2)_R$ symmetry, $D(6, 1, 1)$ are sextet colored fields and $\Phi_i(1, 1, 0)$, $i=0, 1, 2, 3$, are singlets. The two loop diagram for ν^c can be constructed as in the previous cases and it is shown in fig. 4. From (21) we observe that the diagram makes use of the coupling $\lambda_8\bar{F}_{Rj}\bar{F}_{Rj}D$ which is not related to the coupling $\lambda_1 F_{Li}\bar{F}_{Rj}h$ that gives masses to the fermions. Thus there are no constraints on λ_8. Let us then estimate the contribution of this diagram in the minimal GUT version of the model. For $M=10^{16}$ GeV, $\alpha=0.04$ and $\lambda_8 \approx 1$, we get

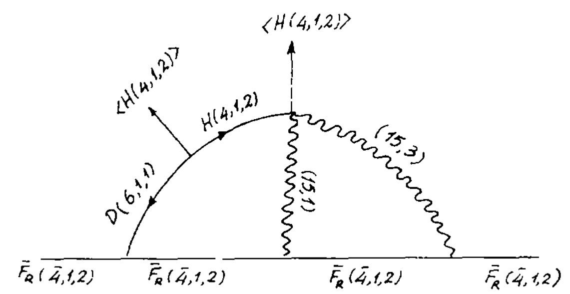

Fig. 4. Two loop contribution to ν^c in the GUT SU(4)×O(4). There is another diagram if we replace $H(4, 1, 2)$ with $\bar{H}(\bar{4}, 1, 2)$.

$$M_{\nu\nu^c} = M^{\text{rad.}} \approx \varepsilon\left(\frac{\alpha}{4\pi}\right)^2 \frac{3}{16}\lambda_8 M_{\text{GUT}}$$
$$= 3\times 10^9\ \text{GeV}\ . \tag{22}$$

We can form now the full neutrino mass matrix that arises from the trilinear couplings as well as from the radiative corrections of the two loop graph of fig. 4. We get

$$(\nu \quad \nu^c \quad \Phi_i)\begin{pmatrix} 0 & m_u & 0 \\ m_u & M^{\text{rad.}} & M \\ 0 & M & \mu \end{pmatrix}\begin{pmatrix} \nu \\ \nu^c \\ \Phi_i \end{pmatrix}, \tag{23}$$

where $M = M_{\text{GUT}} = 10^{16}$ GeV, m_u is the up quark mass matrix and μ here is of the order of the electroweak scale. It is remarkable that if $\mu = 0$, this matrix has three zero eigenvalues corresponding to three light Majorana neutrinos one for each generation, irrespective of the entry $M^{\text{rad.}}$. If however $\mu \neq 0$, then the left handed neutrino masses are given by the approximate formula $m_{\nu_i} = m_{u_i}^2 \mu / M^2$, but still they are negligibly small to be detected. We notice however here that the model becomes more interesting from the point of view of neutrino physics, if the additional singlet fields are not present in the model. Indeed, the contribution from the Witten diagram to the neutrino mass matrix would be sufficient to suppress the left handed neutrino masses within the cosmological bounds. In fact in this case the standard see-saw mechanism would give the eigenmasses $m_{\nu_i} = m_{u_i}^2 / M^{\text{rad.}}$, thus

$$m_{\nu_1} = 1.7\times 10^{-3}\ \text{eV}, \quad m_{\nu_2} = 5\ \text{eV}, \quad m_{\nu_3} = 30\ \text{eV} \tag{24}$$

for m_t around 100 GeV. Thus we conclude that the introduction of extra singlets in the minimal GUT model is not necessary at all. On the contrary, since $M^{\text{rad.}} \ll M$, their absence allows the possibility of having small but perhaps measurable masses for the left handed neutrinos. We think that his point deserves a more detailed analysis which we are planning to present in a future publication.

Let us now turn our discussion to the string version of the above model where as we will see both mechanisms are operative and complementary to each other. As a matter of fact in this case (as well as in most of the string models) in addition to the standard matter fields there appears also a number of neutral singlets Φ_i. Some of them may couple to the right handed neutrinos via Yukawa couplings of the same type as in (21), i.e. $\bar{F}_R H \Phi_i$, leading to an extended see-saw mechanism of the type discussed above. However, in this case this mechanism is not effective for all generations since additional symmetries, remnant from the higher string symmetry, do not allow the presence of this coupling to all three generations. Incorporation of higher nonrenormalizable terms does not appear to be always effective. Thus, it would be very interesting to realize the Witten mechanism for those neutrinos that the corresponding couplings of the type $\bar{F}_R H \Phi_i$ with the singlet fields are missing. Let us enroll the trilinear couplings that are relevant in our case. There are [5]

$$F_{4L}\bar{F}_{5R}h_{12} + (1/\sqrt{2})F_{4R}\bar{F}_{5R}\zeta_2 + \bar{F}_{3R}F_{3L}h_3$$
$$+ \bar{\xi}_1 h_{12} h_3 + \bar{\xi}_1 \xi_4 \Phi_{12} + \tfrac{1}{2}\xi_1 \bar{\xi}_1 \Phi_3\ , \tag{25}$$

where $F_{(3,4)L}$, $\bar{F}_{(3,5)R}$ are fermion fields as before, h_{12}, h_3, F_{4R} play the role of the Higgses and Φ_{12}, ζ_i, ξ_i, are singlets [5]. Notice that the labels 3, 4, 5 appearing in the fields have nothing to do with the generation assignment, but they simply denote the sector they arise from, in the particular construction [5]. Thus we are free to assign the generations according to phenomenological constraints. We choose to assign the third generation in $F_{4L} + \bar{F}_{5R}$. With $\langle \xi_1 \rangle$, $\langle \Phi_{12} \rangle \neq 0$, the $\bar{h}_3$ Higgs field becomes superheavy. Thus, h_{12} plays the role of the two electroweak Higgs doublets which provide masses to the fermions of the third generation $F_{4L} + \bar{F}_{5R}$ through the first term. As in the GUT version of the model [4] one gets the mass relations $m_b = m_\tau$ and $m_t = m_{\nu_4}$. The first relation is the succesfull prediction of old GUTs but the second gives too large a value for the neutrino mass. However the second term $\langle F_{4R}\rangle \bar F_{5R}\bar\zeta_2$ in (25) provides a see-saw mechanism which leads to a massless linear combination of ν_{4L} and $\bar\zeta_2$ which is identified as the left handed neutrino ν_τ. The left handed fermions of the second generation are accommodated in F_{3L} and h_3 multiplets. In particular the lepton doublet is found in

$$h_3 \equiv \begin{pmatrix} \nu_3^0 \\ e_3^- \end{pmatrix} + \begin{pmatrix} h_3^+ \\ \bar h_3^0 \end{pmatrix}, \qquad (26)$$

while the doublet in $\bar F_{3R}$ combines with the second doublet on the RHS of (26) to form a superheavy massive state via the term $\langle \bar F_{3R}\rangle F_{3L} h_3$. The left handed neutrino turns out to be a linear combination of the ν_3^0, Φ_3 and $\bar\xi_4$ as one concludes from the following superpotential terms [5]:

$$\langle h_{12}\rangle \bar\xi_1 h_3 + \langle \Phi_{12}\rangle \bar\xi_1 \bar\xi_4 + \tfrac{1}{2}\langle \xi_1\rangle \bar\xi_1 \Phi_3 , \qquad (27)$$

where $\langle \Phi_{12}\rangle$, $\langle \xi_1\rangle = M_{GUT}$, thus leading again to a light left handed state. Finally, the first generation is accommodated in $F_{1L} + \bar F_{2R}$. It does not receive a mass from trilinear terms but from higher nonrenormalizable terms. Such terms, however, will also yield the unacceptable relationship $m_{\nu_e} = m_u$. Thus one needs a see-saw mechanism to suppress the left handed neutrino mass. There is no coupling with the neutral singlets exactly as in the other two generations. Witten's mechanism, however, can be applied here via the diagram of fig. 5. We can easily estimate the contribution which turns out to be

$$M_{\nu^c} = \lambda_{2R}\varepsilon_D \left(\frac{\alpha}{4\pi}\right)^2 \frac{3}{16}\left(\frac{\langle \bar F_{2R}\rangle^2}{M}\right), \qquad (28)$$

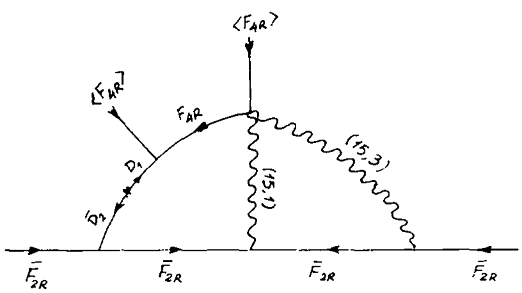

Fig. 5. Two loop contribution to ν^c in the string SU(4)×O(4) model.

where $\lambda_{2R} = g\sqrt{2}$ at the unification scale and ε_D represents the mixing in the color triplet mass matrix [3]. Assuming sensible values for the parameters i.e. $\lambda_{2R} = 0.5$, $\varepsilon_D = 0.1$, $\langle \bar F_{2R}\rangle = 10^{16}$ GeV, $M = 10^{17}$ GeV and $\alpha = 0.04$ [#2], we obtain

$$M_{\nu^c} = 1.52 \times 10^9 \text{ GeV} .$$

Thus we get for the electronic neutrino $m_{\nu_e} = 1.6 \times 10^{-5}$ eV.

7. Conclusions

In the present work, we have shown that the mechanism proposed by Witten provides an economic way of generating the neutrino mass spectrum consistent with the present experimental bounds. We have shown that this mechanism becomes particularly effective in the string models in which the admissible Higgs representations are restricted by symmetry. Such are the E_6 [2] model, the flipped SU(5) [3] and the SU(4)×O(4) model [4,5]. Thus:

(i) in the case of the E_6 model we have shown that there exist two-loop diagrams for the two neutral fields of the $\underline{27}$ which are singlets under the standard W–S group which give them Majorana masses sufficiently large to suppress the left handed neutrinos within the experimental constraints but insufficient to respect the cosmological bounds.

(ii) Correspondingly, in the case of the flipped SU(5) model the same kind of diagram produces a large Majorana mass for the ν^c field which now is a member of the $\underline{10}$ dimensional representation. These masses however are not sufficiently large since they are proportional to the down quark masses, thus again only the experimental bound is respected. It is possible however, in the GUT version of the model, to respect both bounds if neutral fields which are singlets under the whole gauge group are introduced [3]. These singlets arise naturally in the string version [9].

(iii) In the case of the GUT version of the SU(4)×O(4) model [4], one of the couplings which participate in the two-loop diagram, contrary to the cases considered previously, does not depend either

[#2] The values used for $\langle \bar F_{2R}\rangle$, M, and α have been dictated by a renormalization group analysis that has been performed for this particular model.

on the up or on the down quark Yukawa coupling. Therefore, there are no constraints on this coupling and the corresponding contribution can be larger than those of the previous cases. The left handed neutrino masses are sufficiently small but still measurable satisfying the cosmological bound $\sum m_{\nu_i} < 50$ eV, with a natural hierarchy $(m_{\nu_e}, m_{\nu_\mu}, m_{\nu_\tau})$. Its string variant [5] however, is characterized by the fact that all three left handed neutrinos get negligibly small masses.

Acknowledgement

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