Radiative neutrino decay in E_6 models

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The existence of relatively light ($\lesssim 1$ TeV) exotic fermions and right-handed currents present in E_6 grand unified theories can lead to an enormous enhancement in the radiative decay of neutrinos by many orders of magnitude. For neutrino masses in the keV range this allows for the possibility of evading the cosmological bound resulting from the shape of spectrum of the microwave background.

Recently, interest has been renewed[1,2] in the possibility of avoiding the cosmological/astrophysical bounds[3] on the radiative decay of a heavy neutrino ν_H. Part of this work has resulted from the speculation by Stecker[4] that the increase in the cosmic photon flux (at energies of $\simeq 7.4$ eV) may be due to the radiative decay of a heavy neutrino ($\nu_H \to \nu_L + \gamma$) with a lifetime in the range $(3-16)\times 10^{15}$ yr.

As pointed out by several authors,[5] it is impossible to obtain such short lifetimes for radiative neutrino decays in the $SU(2)_L \times U(1)_Y$ standard model (SM) for neutrinos in this mass range. For even heavier neutrinos the lifetime constraints become even more severe, $\tau \lesssim 10^4-10^6$ sec for m_H between 100 eV and 1 GeV (Ref. 3). Clearly the SM cannot achieve such short lifetimes. The authors of Refs. 1 and 2 have investigated the possibility that right-handed currents (RHC's), such as exist in left-right-symmetric models,[6] may lead to an enhancement of ν_H radiative decay. Chattopadhyay and Pal[2] conclude, in the class of models they examined, that while a large enhancement does occur in these models the lifetimes so obtained are still too long by approximately a factor of 10^6 even if a heavy fourth generation of fermions exists.

In this paper we wish to examine the decay $\nu_H \to \nu_L + \gamma$ in a class of electroweak models based on E_6 grand unified theories.[7] Interest in the phenomenology of such models has recently been renewed due to the flowering of superstring theory.[8] As has been shown in our earlier work,[9] the existence of RHC's as well as flavor-changing neutral currents and exotic fermions can lead to very substantial enhancements of flavor-changing radiative decays (such as $\mu \to e\gamma$) when the heavy exotic fermions are on the internal lines. We will see that in E_6 models very substantial enhancements of the process $\nu_H \to \nu_L + \gamma$ are possible for reasonable values of the model parameters.

Let us write the leptons of the low-energy sector of our E_6 model in the form

$$\eta^0_{L,R} = \begin{bmatrix} \nu^0 \\ N^0 \end{bmatrix}_{L,R}, \quad \epsilon^0_{L,R} = \begin{bmatrix} e^0 \\ E^0 \end{bmatrix}_{L,R}, \tag{1}$$

where the superscript 0 denotes the weak-interaction-eigenstate basis. In this basis the charged-current weak interactions can be written as

$$\frac{g}{2\sqrt{2}}[\bar{\nu}^0\gamma_\mu(1-\gamma_5)e^0+\bar{N}^0\gamma_\mu(1-\gamma_5)E^0 + \bar{N}^0\gamma_\mu(1+\gamma_5)E^0]W^\mu + \text{H.c.}, \tag{2}$$

where T_+ represents an isospin-raising operator. Transforming to the mass-eigenstate basis, Eq. (2) becomes

$$\frac{g}{2\sqrt{2}}(\bar{\nu},\bar{N})\gamma_\mu(V-A\gamma_5)\begin{bmatrix} e \\ E \end{bmatrix}W^\mu + \text{H.c.}, \tag{3}$$

where we have defined the matrices

$$V = V_L + V_R, \quad A = V_L - V_R \tag{4}$$

with $V_{L,R}$ given by

$$V_L = U_L^\nu U_L^{e\dagger}, \quad V_R = U_R^\nu \begin{bmatrix} 0 & 0 \\ 0 & I \end{bmatrix} U_R^{e\dagger}. \tag{5}$$

The matrices $U^{\nu,e}_{L,R}$ rotate the fields $\eta^0_{L,R}$ and $\epsilon^0_{L,R}$ to the mass-eigenstate basis.

Now we can write the matrix element for $\nu_H \to \nu_L + \gamma$ in the standard form

$$M = C\bar{\nu}_L\sigma_{\mu\nu}\epsilon^\mu q^\nu(v - a\gamma_5)\nu_H \tag{6}$$

which leads to the decay rate

$$\Gamma(\nu_H \to \nu_L + \gamma) = \frac{C^2}{8\pi}M_H{}^3(1-M_L{}^2/M_H{}^2)^3 \times(|v|^2+|a|^2). \tag{7}$$

As discussed above, the dominant contribution to the above process comes from the exotic-lepton intermediate state as shown in Fig. 1 for which we obtain, assuming Dirac neutrinos,

$$C = \frac{eG_F M_W}{8\sqrt{2}\pi^2} \tag{8}$$

and

$$\begin{aligned} v &= \sum_i G(\delta_i)[(V_L^*)_{iH}(V_R)_{iL} + (V_L)_{iL}(V_R^*)_{iH}], \\ a &= \sum_i G(\delta_i)[(V_L^*)_{iH}(V_R)_{iL} - (V_L)_{iL}(V_R^*)_{iH}] \end{aligned} \tag{9}$$

with $\delta_i \equiv M_i / M_W$ (with M_i being the mass of the intermediate charged exotic lepton) and the function $G(\delta)$ is given by

$$G(\delta)=\delta(1-\delta^2)^{-2}(4-5\delta^2+\delta^4+6\delta^2\ln\delta) \ . \tag{10}$$

Combining this with Eq. (1) above yields the decay rate for Dirac neutrinos

$$\Gamma(\nu_H \to \nu_L+\gamma)\Big|_{\rm Dirac}=\frac{\alpha G_F{}^2 M_W{}^2 M_H{}^3}{64\pi^4}\left[1-\frac{M_L{}^2}{M_H{}^2}\right]^3 \sum_i |G(\delta_i)|^2[\tfrac{1}{4}|(V_L^*)_{iH}(V_R)_{iL}|^2+\tfrac{1}{4}|(V_L)_{iL}(V_R^*)_{iH}|^2] \tag{11}$$

or numerically

$$\tau_{\rm Dirac}=(6.15\times 10^5\ {\rm sec})\left[\frac{1\ {\rm keV}}{M_H}\right]^3\left[1-\frac{M_L{}^2}{M_H{}^2}\right]^{-3}\left[\sum_i |G(\delta_i)|^2[\tfrac{1}{4}|(V_L^*)_{iH}(V_R)_{iL}|^2+\tfrac{1}{4}|(V_L)_{iL}(V_R^*)_{iH}|^2]\right]^{-1} . \tag{12}$$

The function $G(\delta)$ is shown in Fig. 2.

In the case of Majorana neutrinos, as discussed in Ref. 2, there are additional contributions arising from the charged conjugate intermediate states (i.e., $W^- E_i^c$). This modifies Eq. (9):

$$\begin{aligned} v=\sum_i G(\delta_i)\{&(V_L^*)_{iH}(V_R)_{iL}+(V_L)_{iL}(V_R^*)_{iH}\\ &-e^{i\beta}[(V_L^*)_{iL}(V_R)_{iH}+(V_L)_{iH}(V_R^*)_{iL}]\}\ ,\\ a=\sum_i G(\delta_i)\{&(V_L^*)_{iH}(V_R)_{iL}-(V_L)_{iL}(V_R^*)_{iH}\\ &-e^{i\beta}[(V_L^*)_{iL}(V_R)_{iH}-(V_L)_{iH}(V_R^*)_{iL}]\}\ , \end{aligned} \tag{9'}$$

where β is the relative phase of the ν_H and ν_L fields. To make definitive calculations in the Majorana case requires knowledge of the phase β. For comparable values of the V's the additional terms could lead to a substantial suppression of the $\nu_H \to \nu_L+\gamma$ decay.

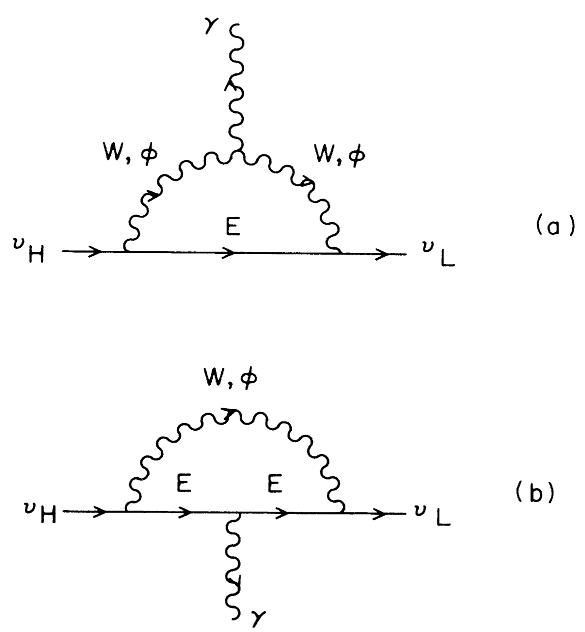

FIG. 1. Feynman diagrams giving the leading contribution to ν_H radiative decay in E_6 models.

Figure 3 shows $\tau_{\rm Dirac}$ for $M_H = 1$ keV and $M_L = 0$ for the simple case of a single intermediate exotic charge lepton omitting the mixing factor as a function of δ. Apart from mixing this is a reasonable approximation since we do not expect significant Glashow-Iliopoulos-Maiani-type cancellations for exotic charged leptons with such large masses. We see that as δ increases there is a very substantial decrease in the value of $\tau_{\rm Dirac}$. Present SLAC PEP and DESY PETRA data[10] constrain $\delta \gtrsim 0.28$ so that for this simple case we expect $\tau_{\rm Dirac} \lesssim 6\times 10^5$ sec for $M_H = 1$ keV (neglecting mixing). For $M_H \simeq 14.8$ eV this implies that $\tau_{\rm Dirac} \lesssim 6\times 10^3$ yr, where mixing is again neglected. We see, however, that for $(V_{L,R})$'s $\sim 10^{-3}$ we can obtain lifetimes in the desired range ($\sim 10^{15}$–10^{16} yr). For very heavy ν_H (10 MeV–1 GeV) these same kinds of mixing values continue to satisfy the cosmological bound. However, for ν_H in the 100 eV–10 MeV region we cannot simultaneously allow for a second $\simeq 14.8$ eV neutrino with the above lifetime for the same magnitude of the mixing matrix elements. Thus if V's $\sim 10^{-3}$ and the excess cosmic photons originate from the $\nu_H \to \nu_L+\gamma$ process then there can be no further heavier neutrino in this model that can decay dominantly into $\nu_L+\gamma$ unless its mass exceeded $\simeq 10$ MeV. For such heavy masses, however, we might expect a neutrino to decay by other processes such as $\nu_H \to \nu_L e^+ e^-$.

If we ignore the Stecker hypothesis and make the rather strict demand that all neutrinos in the mass range 100

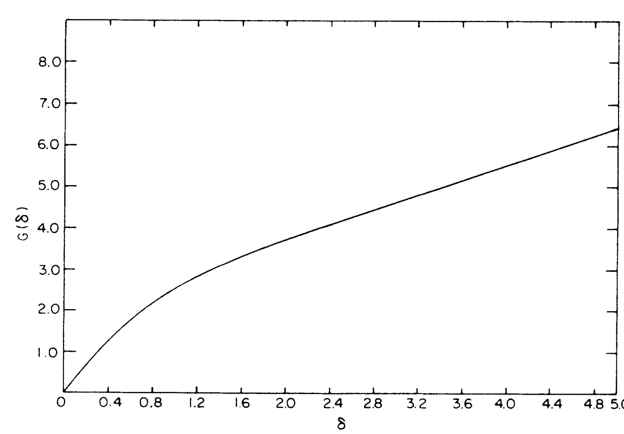

FIG. 2. The function $G(\delta)$.

eV–1 GeV have $\tau \lesssim 10^4$ sec, this would imply (for $\delta=1$, say) the bound $M_H \gtrsim 50$ keV with V's$\simeq 0.1$ ($\gtrsim 1$ MeV with V's$\simeq 0.01$). These limits are not weakened very much by taking larger values of δ unless δ is taken to be extremely and perhaps unnaturally large, e.g., for $\delta=4$ we obtain the bound $M_H \gtrsim 27$ keV with V's$\simeq 0.1$ ($\gtrsim 0.60$ MeV with V's$\simeq 0.01$). Note that looser bounds[3] actually apply for ν_H in the more restricted mass range 100 eV–100 keV:

$$\tau < 2\times 10^6 \{1+[(1\text{ keV})/M_H]^2\}^{-1/2}\text{ sec} .$$

For $\delta \simeq 1$ this would imply that (with V's$\simeq 0.1$) $M_H \gtrsim 3.5$ keV. This value is quite interesting in that if ν_1 is in the $\simeq 20$ eV mass range[11] and neutrino masses scale as $M_2 \simeq (M_\mu/M_e)M_1$, $M_3 \simeq (M_\tau/M_e)M_1$, as they do in some models,[12] then $M_2 \simeq 4.1$ keV and $M_3 \simeq 70$ keV and such neutrinos could decay radiatively and still avoid the astrophysical bounds if mixings are sufficiently large.

In conclusion we have shown that the existence of RHC's and exotic fermions in E_6 theories can lead to a very substantial enhancement in the rate for the radiative decay $\nu_H \to \nu_L \gamma$. If Stecker's hypothesis is correct, ν_H lifetimes in the required range are obtained for small mixings $\sim 10^{-3}$. If $\nu_H = \nu_2$ in this scenario and mixings are roughly generation independent then $M_3 \gtrsim 10$ MeV if ν_3 decays dominantly by photon emission. If, on the other hand, $\nu_H = \nu_3$ and $\nu_L = \nu_1$ or ν_2, then there is no difficulty from cosmological constraints.

If Stecker's hypothesis is ignored, constraints can be placed on ν masses (as a function of the mixing parameters) using the astrophysical bounds. These constraints may have some impact on models for the fermion masses.

Note added. After completion of this work our attention was drawn to a paper by Enqvist and Maalampi,[13] who also consider radiative ν decay in superstring E_6 theories. These authors use the Yukawa couplings from the superpotential to induce a decay rate proportional to the down-quark mass instead of a ν mass. This produces lifetimes of order 10^{20}–10^{24} sec for $m_{\nu_\mu} \simeq 50$ eV. We obtain similar lifetimes if V's $\sim 10^{-3}$.

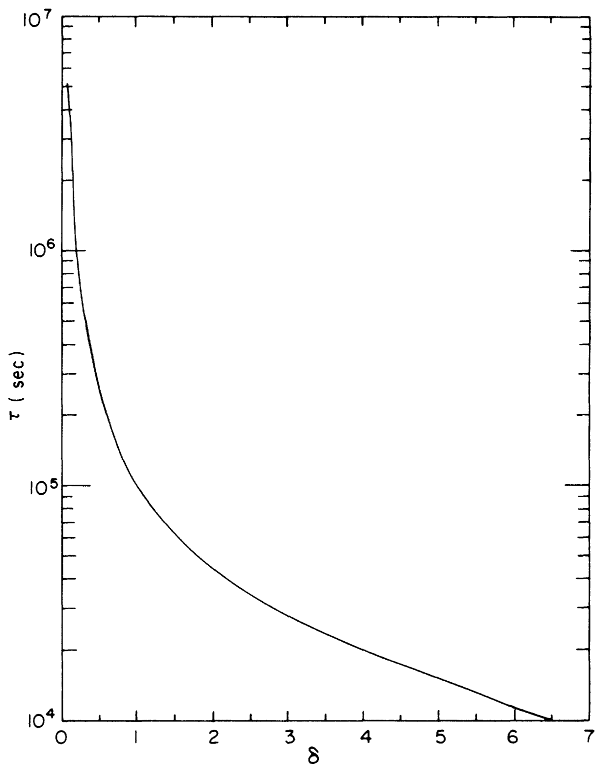

FIG. 3. Lifetime of a Dirac ν_H with mass of 1 keV omitting mixing factor as a function of δ.

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