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Neutral massive leptons in an SO(10) model with massless neutrinos

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The neutral massive leptons expected in SO(10) have been studied in a model which permits neutrinos to be massless. The mixing of these leptons with ordinary neutrinos introduces violations of weak universality. Three massive leptons occur: N_1, coupling to μ and ν_μ with strength (0.026 GeV/M_{N_1}) relative to the ordinary weak coupling; N_2, coupling to τ and ν_τ with relative strength (1.8 GeV/M_{N_2}); and N_3, coupling to μ and ν_μ with relative strength (1.8 GeV/M_{N_3}) and to τ and ν_τ with relative strength (8 GeV/M_{N_3}). Their masses are bounded from below by 0.37, 6, and 25 GeV, respectively. The prospects for observing the neutral massive leptons in neutrino neutral-current interactions, in W and Z decays, and in τ, c, and b decays are discussed.

I. INTRODUCTION

Unified models of the strong and electroweak interactions have the appealing feature that they combine quarks and leptons into multiplets of a higher symmetry.[1,2] The simplest model, SU(5), makes use of two distinct multiplets (5- and 10-dimensional) for the observed fermions. These multiplets may be incorporated into a single 16-dimensional spinor representation of the group SO(10).[3] The price one pays for introducing SO(10) is an additional, as yet unobserved SU(5) singlet, since $16=5^*+10+1$. This singlet, which we shall call N, would correspond to a neutral lepton. If the neutrino were a massive Dirac particle, this singlet would correspond to a right-handed neutrino.

The observation that the neutrino's mass is so much less than that of other particles has led to the suggestion[4] that a large Majorana mass for the SU(5) singlet forces the neutrino mass to be small. The Majorana masses of the observed neutral leptons would then be the eigenvalues of the mass matrix

$$\mathscr{M}=\begin{bmatrix} 0 & m \\ m & M \end{bmatrix}, \tag{1}$$

where m is of the order of ordinary Dirac masses, and M is the large Majorana mass. Here the neutrino mass would be $\approx m^2/M$. With $m\sim 1$ GeV and $m^2/M \lesssim$ (tens of eV), M would exceed 10^8 GeV, and the heavy neutral leptons would be unobservable. Variations on this theme also have been suggested, permitting dramatically smaller values of M.[5]

The presence in a theory of very massive fermions is known to constrain the ways in which a symmetry can break down.[6] The SU(5)-singlet fermions N belonging to a 16-plet of SO(10) carry a charge (we shall call it χ) associated with the U(1) in

$$\mathrm{SO}(10)\to\mathrm{SU}(5)\times\mathrm{U}(1)_\chi . \tag{2}$$

If the SU(5)-singlet fermions N are very massive, the $\mathrm{U}(1)_\chi$ must be broken at a scale comparable to their mass.[7]

Experimentally it turns out that there are very few constraints on the scale of $\mathrm{U}(1)_\chi$ breaking. Mechanisms for breaking $\mathrm{SU}(2)_W\times\mathrm{U}(1)_{Y_W}\times\mathrm{U}(1)_\chi$ can be introduced which permit the mass of the neutral boson coupled to $\mathrm{U}(1)_\chi$ to be as low as ≈ 200 GeV.[8–10] The question then arises whether there are corresponding mechanisms for fermion-mass generation which allow the SU(5)-singlet fermions N also to be light.

In this paper we investigate a model in which the neutral-heavy-lepton masses are indeed allowed to be light, and experimentally accessible.[11] The model is based on a mechanism introduced by Wyler and Wolfenstein[12] which allows the light ("left-handed") neutrinos to be massless to all orders. This is accomplished by introducing an SO(10)-singlet fermion S, which is allowed to mix in a prescribed way with the neutral 16-plet members. A related approach was attempted in Ref. 13, and the mechanism has been suggested earlier.[14]

In the present model, the neutral-lepton masses are bounded from below only by the observed universal strength of the weak interactions in various processes. We find there are three neutral leptons corresponding to the three generations. They all have Dirac masses. All masses are to be regarded as uncertain by a factor of 3 unless otherwise mentioned.

The lepton N_1 has a mass of at least 0.37 GeV. (This is a strict limit.) It couples to μ^- via the $V-A$ charged current and to ν_μ via the neutral weak current with strengths (0.026 GeV/M_{N_1}) of the ordinary ones. As a result, one estimates its lifetime to be about $10^{-(8\pm 1)}$ sec for $M_{N_1}\approx 1$ GeV, decreasing roughly as ${M_{N_1}}^{-3.3}$. It could decay to $\mu^-\pi^+$, and should be looked for in muon-neutrino interactions. It can also be produced in any source of massive weak currents, such as in the decays $\tau\to\nu_\tau N_1\mu$,

$c\to sN_1\mu$, $F\to N_1\mu$, $b\to cN_1\mu$, $W\to N_1\mu$, or $Z\to N_1\nu_\mu$. In the first three decays, the final states should be investigated for $\mu\pi$ resonances, and μF resonances may show up in the last three as well.

The lepton N_2 has a mass of at least ≈ 6 GeV. It couples to τ^- via the $V-A$ charged current and to ν_τ via the neutral weak current with strengths ($1.8\ \mathrm{GeV}/M_{N_2}$) of the ordinary ones. It might first show up in W or Z decays.

The lepton N_3 has a mass of at least ≈ 25 GeV. It couples to τ^- via the $V-A$ charged current and to ν_τ via the neutral current with strengths ($8\ \mathrm{GeV}/M_{N_3}$) of the ordinary ones, and to μ^- via the $V-A$ charged current and ν_μ via the neutral current with strengths ($1.8\ \mathrm{GeV}/M_{N_3}$) of the ordinary ones. It could be produced in high-energy ν_μ interactions, or in W and Z decays.

The parameters for N_2 and N_3 are dependent on the t-quark mass, which we shall take for the purposes of the subsequent discussion to be 25 GeV.

The estimates given above are based on the following experimental constraints, which we shall discuss in more detail.

(1) In comparing the strength of ^{14}O β decay and muon decay, one is permitted only a 1.5% deviation from weak universality.

(2) It is assumed that the lifetime of the τ lepton can be measured in the next few years to be within 10% of its standard value in the $V-A$ theory. The bounds on N_2 masses and couplings follow from this result. Conversely, *a natural framework exists for detectable violations of weak universality in* τ *decays.*

(3) The ratio

$$\Gamma(\pi^\pm\to e^\pm\nu)/\Gamma(\pi^\pm\to\mu^\pm\nu)\ ,$$

recently measured more accurately,[15] provides a useful constraint, somewhat more powerful in our model than the ^{14}O β-decay relation, and tests weak universality to the 1% level.

Whenever neutral heavy leptons are present, there is the possibility of induced $\mu\to e\gamma$ decays. We find the prediction for this process to be at the level of $B(\mu\to e\gamma)\lesssim 8\times 10^{-17}$, safely below present bounds[16] (indeed impossibly small). The processes $\tau\to e\gamma$ and $\tau\to\mu\gamma$ are predicted to occur with branching ratios of 10^{-12} or less.

We discuss the model for fermion masses and the corresponding mixing scheme in Sec. II. The constraints on parameters in this model (which amount to constraints on N_i masses) arising from weak universality are treated in Sec. III. Consequences for lifetimes, branching ratios, and production processes (neutrino interactions, τ, c, and b decays, W and Z decays, etc.) are mentioned in Sec. IV. The radiative decays $\mu\to e\gamma$, $\tau\to e\gamma$, $\tau\to\mu\gamma$ are treated in Sec. V. Our conclusions are contained in Sec. VI.

II. A MODEL FOR FERMION MASSES

There appears no convincing evidence for neutrino masses at present.[17] A model in which a neutrino ν may remain massless to all orders, while the SU(5) singlet N belonging to SO(10) 16-plets acquires a mass, can be constructed[12,14] by introducing an SO(10)-singlet fermion S and a Higgs field h belonging to a 16-plet representation of SO(10). Its vacuum expectation value $\langle h\rangle$ is assumed to belong to a singlet representation of SU(5). The coupling

$$\mathcal{L}_h = g(\bar\psi h S + \mathrm{H.c.}),\quad \psi=\underline{16}\ \text{fermion}\ , \tag{3}$$

then leads to a Dirac mass $g\langle h\rangle$ for the heavy neutral lepton N, while the neutrino ν remains massless.

This model may be generalized to three generations. Let us denote the SO(10) 16-plets and singlets by

$$\psi_i\in 16,\quad S_i\in 1,\quad i=1,2,3\ . \tag{4}$$

We introduce three complex Higgs fields ϕ_a ($a=1,2,3$) belonging to 10-plets of SO(10), and the 16-plet Higgs field h mentioned above. The Lagrangian is

$$\mathcal{L}_Y = \hat a_1\psi_1\psi_2\phi_1 + \hat a_2\psi_2\psi_3\phi_2 + \hat a_3\psi_3\psi_3\phi_3 + h^\dagger\sum_{i=1}^{3}\beta_i S_i\psi_i + \mathrm{H.c.} \tag{5}$$

We ignore CP violation, hence all Yukawa couplings and vacuum expectation values are real. The terms in (5) have been proposed before,[18] except with $\langle h\rangle$ having a large vacuum expectation value ($\approx 10^{16}$ GeV). The first three terms may be justified on the basis of discrete symmetries, and follow from certain composite models.[19]

The corresponding vacuum expectation values for the 10-plet members are different, depending on whether masses are being given to particles whose left-handed states are $I_{3W}=+\frac{1}{2}$ or $-\frac{1}{2}$ members of weak isodoublets. Thus, u quarks and neutrinos would receive contributions from

$$\langle\phi_a\rangle_{I_{3W}=+1/2}\equiv v_a^u\quad (a=1,2,3)\ , \tag{6}$$

while d quarks and charged leptons would receive contributions from

$$\langle\phi_a\rangle_{I_{3W}=-1/2}\equiv v_a^d\quad (a=1,2,3)\ . \tag{7}$$

It is easiest to discuss first the masses for charged fermions. They are the eigenvalues of the mass matrices

$$M^{u,(d\ \mathrm{or}\ l)} = \begin{bmatrix} 0 & \hat a_1 v_1^{u,d} & 0 \\ \hat a_1 v_1^{u,d} & 0 & \hat a_2 v_2^{u,d} \\ 0 & \hat a_2 v_2^{u,d} & \hat a_3 v_3^{u,d}\end{bmatrix}\ . \tag{8}$$

The masses of d quarks (d,s,b) and charged leptons (e,μ,τ) are equal at the unification scale, as in ordinary SU(5). The phenomenology of this model is not entirely satisfactory, but modest distortions (by factors of no more than 3) permit one to accommodate the observed masses.[18]

We shall need, in particular, the mass matrix of $I_{3W}=+\frac{1}{2}$ fermions. For u quarks, we may write it as

$$M^u = \begin{bmatrix} 0 & a_1 & 0 \\ a_1 & 0 & a_2 \\ 0 & a_2 & a_3\end{bmatrix}\ . \tag{9}$$

The eigenvalues λ_i of M^u give the physical masses of u,

c, and t quarks. Since

$$\lambda_1\lambda_2\lambda_3=\det M^u=-a_1{}^2a_3 \ , \tag{10}$$

$$\lambda_1+\lambda_2+\lambda_3=\mathrm{tr}M^u=a_3 \ , \tag{11}$$

if we demand by convention $\lambda_3=m_t>0$ and hence that $a_3>0$, we find that one of λ_1,λ_2 must be negative. Furthermore, in the limit that $|\lambda_1| \ll |\lambda_2| \ll |\lambda_3|$, one can show that

$$\lambda_2\lambda_3\approx -a_2{}^2 \tag{12}$$

so that it is λ_2 which must be negative, and

$$\lambda_1=m_u, \ \ \lambda_2=-m_c, \ \ \lambda_3=m_t \ . \tag{13}$$

The eigenvalues λ_i of the mass matrices $M^{u,d}$ are to be viewed as masses evaluated at the grand unification scale. In principle, they should be reevaluated at ordinary energies by standard renormalization-group methods for comparison with experiment. At the grand unification scale one expects $m_b=m_\tau$, $m_s=m_\mu$, $m_d=m_e$. At ordinary energies one then predicts[20]

$$m_b/m_\tau\approx 3 \ \ \text{(satisfactory)} \ , \tag{14}$$

$$m_s/m_\mu\approx 3 \ \ \text{(3 too high?)} \ , \tag{15}$$

$$m_d/m_e\approx 3 \ \ \text{(3 too low?)} \ . \tag{16}$$

On the average, the (quark mass)/(lepton mass) ratio appears to be renormalized by a factor of 3 in passing from the unification scale to observable energies. We shall assume this to be the case in relating u,c,t masses to neutral-lepton masses, and thus shall evaluate a_1, a_2, and a_3 using physical quark masses *divided by 3.* In view of the deviations in (14)–(16), we regard these mass estimates as uncertain by a factor of 3.

We assume that at ordinary energies,

$$m_u=5 \text{ MeV}, \ \ m_c=1.2 \text{ GeV}, \ \ m_t=25 \text{ GeV} \ . \tag{17}$$

Then, taking account of the factor of 3 mentioned above, we find for the purpose of evaluating neutral-heavy-lepton masses that

$$a_1=\sqrt{m_u m_c}/3=26 \text{ MeV} \ , \tag{18}$$

$$a_2=\sqrt{m_t m_c}/3=1.8 \text{ GeV} \ , \tag{19}$$

$$a_3=(m_t-m_c+m_u)/3=8 \text{ GeV} \ . \tag{20}$$

The mass matrix for neutral leptons may now be written in block form as

$$M^N=\begin{array}{c} \begin{matrix} \nu_L & S_L & N_L^c \end{matrix} \\ \begin{bmatrix} 0 & 0 & M^u \\ 0 & 0 & B \\ M^u & B & 0 \end{bmatrix} \end{array} , \tag{21}$$

where M^u is the 3×3 matrix as defined in Eq. (9) with a_1, a_2, and a_3 given by (18)–(20), and B is a diagonal 3×3 matrix of the form

$$B=\langle h\rangle \begin{bmatrix} \beta_1 & & \\ & \beta_2 & \\ & & \beta_3 \end{bmatrix} \equiv \begin{bmatrix} B_1 & & \\ & B_2 & \\ & & B_3 \end{bmatrix} . \tag{22}$$

This matrix will have three zero-mass eigenvalues, corresponding to the three massless neutrinos, and three eigenvalues of $\pm M_{N_1}$, $\pm M_{N_2}$, $\pm M_{N_3}$, corresponding to three Dirac masses.[12,21]

In what follows, on the basis of constraints from weak universality, we shall argue that

$$\begin{aligned} &a_1/M_{N_1}\ll 1, \ \ a_1/M_{N_2}\ll 1, \ \ a_1/M_{N_3}\ll 1 \ , \\ &a_2/M_{N_2}\ll 1, \ \ a_2/M_{N_3}\ll 1 \ , \\ &a_3/M_{N_3}\ll 1 \ . \end{aligned} \tag{23}$$

In these approximations, we find

$$M_{N_1}\approx B_1\left[1+\frac{1}{2}\frac{a_1{}^2}{B_1{}^2}\right] , \tag{24}$$

$$M_{N_2}\approx B_2\left[1+\frac{a_1{}^2+a_2{}^2}{2B_2{}^2}\right] , \tag{25}$$

$$M_{N_3}\approx B_3\left[1+\frac{a_2{}^2+a_3{}^2}{2B_3{}^2}\right] . \tag{26}$$

The corresponding heavy-lepton eigenstates are

$$\chi_1^{\pm}=\frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ a_1/B_1 \\ 0 \\ 1 \\ 0 \\ 0 \\ \pm 1 \\ 0 \\ 0 \end{bmatrix} , \ \ \chi_2^{\pm}=\frac{1}{\sqrt{2}}\begin{bmatrix} a_1/B_2 \\ 0 \\ a_2/B_2 \\ 0 \\ 1 \\ 0 \\ 0 \\ \pm 1 \\ 0 \end{bmatrix} , \ \ \chi_3^{\pm}=\frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ a_2/B_3 \\ a_3/B_3 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ \pm 1 \end{bmatrix} , \tag{27}$$

where we neglect terms of order $(a_i/B_j)^2$. These are orthogonal (to the desired order) to the massless, mutually orthogonal eigenstates

$$\nu_1=\begin{pmatrix} 1-\dfrac{a_1^2}{2B_2^2} \\ 0 \\ 0 \\ 0 \\ -a_1/B_2 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad \nu_2=\begin{pmatrix} 0 \\ 1-\dfrac{a_1^2}{2B_1^2}-\dfrac{a_2^2}{2B_3^2} \\ 0 \\ -a_1/B_1 \\ 0 \\ -a_2/B_3 \\ 0 \\ 0 \\ 0 \end{pmatrix},$$

$$\nu_3=\begin{pmatrix} 0 \\ 0 \\ 1-\dfrac{a_2^2}{2B_2^2}-\dfrac{a_3^2}{2B_3^2} \\ 0 \\ -a_2/B_2 \\ -a_3/B_3 \\ 0 \\ 0 \\ 0 \end{pmatrix}. \tag{28}$$

The charged- and neutral-current interactions are (again, to the order of interest)

Charged Neutral

$$J_\mu^e=\bar{e}_L\gamma_\mu\mathscr{N}_L^e,\quad J_\mu^{\nu_e}=\overline{\mathscr{N}}_L^e\gamma_\mu\mathscr{N}_L^e\ , \tag{29a}$$

$$J_\mu^\mu=\bar{\mu}_L\gamma_\mu\mathscr{N}_L^\mu,\quad J_\mu^{\nu_\mu}=\overline{\mathscr{N}}_L^\mu\gamma_\mu\mathscr{N}_L^\mu\ , \tag{29b}$$

$$J_\mu^\tau=\bar{\tau}_L\gamma_\mu\mathscr{N}_L^\tau,\quad J_\mu^{\nu_\tau}=\overline{\mathscr{N}}_L^\tau\gamma_\mu\mathscr{N}_L^\tau\ , \tag{29c}$$

where

$$\mathscr{N}_L^e\equiv\nu_L^e\left[1-\frac{a_1^2}{2B_2^2}\right]+N_{2L}\frac{a_1}{B_2}\ , \tag{30a}$$

$$\mathscr{N}_L^\mu\equiv\nu_L^\mu\left[1-\frac{a_1^2}{2B_1^2}-\frac{a_2^2}{2B_3^2}\right]+N_{1L}\frac{a_1}{B_1}+N_{3L}\frac{a_2}{B_3}\ , \tag{30b}$$

$$\mathscr{N}_L^\tau\equiv\nu_L^\tau\left[1-\frac{a_2^2}{2B_2^2}-\frac{a_3^2}{2B_3^2}\right]+N_{2L}\frac{a_2}{B_2}+N_{3L}\frac{a_3}{B_3}\ . \tag{30c}$$

Here we have ignored small ratios of charged-lepton masses associated with rotations induced by the charged-lepton mass matrix. More precise expressions for charged-current couplings are important for $\mu\to e\gamma$ and related processes.

III. CONSTRAINTS FROM WEAK UNIVERSALITY

A. Comparison of $^{14}O\to{}^{14}Ne\nu$ and $\mu\to e\nu\bar{\nu}$

In a six-quark model, charged weak currents can be written as

$$J_{\text{quarks}}^\mu=(\bar{u}\,\bar{c}\,\bar{t})_L\gamma^\mu\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb}\end{bmatrix}\begin{bmatrix} d \\ s \\ b\end{bmatrix}\ . \tag{31}$$

Comparison of $^{14}O\to{}^{14}Ne\nu$ and $\mu\to e\nu\bar{\nu}$ in the standard model, where μ couples universally to the weak current, indicates[22]

$$|V_{ud}|=0.9737\pm0.0025\ . \tag{32}$$

In our version, where the μ-ν_μ coupling can be diminished as a result of mixing, this must be transcribed [see Eqs. (29b) and (30b)] to read

$$|V_{ud}|=(0.9737\pm0.0025)\left[1-\frac{a_1^2}{2B_1^2}-\frac{a_2^2}{2B_3^2}\right]\ . \tag{33}$$

We will assume

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1\ . \tag{34}$$

An upper bound on $a_1^2/(2B_1^2)+a_2^2/(2B_3^2)$ then follows if we can place a *lower* bound on $|V_{ud}|$. This, in turn, requires an upper bound on $|V_{us}|^2+|V_{ub}|^2$.

The analysis of K_{e3} and hyperon decays implies[22]

$$|V_{us}|=0.219\pm0.002\ , \tag{35}$$

if we assume that the electron coupling strength is universal. To the accuracy required, we shall see that this is true.

Analysis of lepton spectra in b decays indicate that b decays mostly to c, not to u (Ref. 23):

$$|V_{ub}/V_{cb}|\le0.14\ . \tag{36}$$

Moreover the study of charmed-particle production in neutrino reactions indicates[22]

$$|V_{cd}|^2+|V_{cs}|^2\gtrsim\tfrac{1}{2} \tag{37}$$

or

$$|V_{cb}|\le0.7\ , \tag{38}$$

so

$$|V_{ub}|\le0.1\ . \tag{39}$$

Thus we infer, at the 2σ level for (35),

$$|V_{ud}|\ge0.9715\ , \tag{40}$$

or, using 2σ limits in (33),

$$\frac{a_1^2}{B_1^2}+\frac{a_2^2}{B_3^2}\le1.5\%\ . \tag{41}$$

This is the degree to which weak universality is permitted to be violated in muon decay. From (18), (19), and (41), we infer

$$B_1 \gtrsim 200 \text{ MeV}/c^2 , \tag{42}$$

$$B_3 \gtrsim 15 \text{ GeV}/c^2 . \tag{43}$$

As will be seen below, one can improve the bound (42) via direct experimental searches, and one can also do better than (43) in principle by measuring the τ lifetime accurately, as we now show.

B. The τ lifetime

Let us assume that in the next few years, the τ lifetime can be measured to lie within 10% of its value in the standard model.[24] Then, from Eqs. (29c) and (30c), we would set the bound

$$\frac{a_2{}^2}{B_2{}^2}+\frac{a_3{}^2}{B_3{}^2} \le 0.1 . \tag{44}$$

We shall actually use this value, together with (19) and (20), to infer that

$$B_2 \ge 5.8 \text{ GeV} , \tag{45}$$

$$B_3 \ge 25 \text{ GeV} . \tag{46}$$

The result (45) justifies, *a posteriori,* the universality assumption for electrons, since deviations are proportional to $a_1{}^2/B_2{}^2 \lesssim 2\times 10^{-5}$.

C. Comparison of $\pi\to e\nu$ and $\pi\to\mu\nu$

A recent measurement[15] finds

$$R \equiv \frac{\Gamma(\pi\to e\nu)}{\Gamma(\pi\to\mu\nu)} = (1.218\pm 0.014)\times 10^{-4} \tag{47}$$

(undetected photons are included in these rates), while theoretically, with our weak currents, after radiative corrections,

$$R = (1.233\times 10^{-4})\left[1+\frac{a_1{}^2}{B_1{}^2}+\frac{a_2{}^2}{B_3{}^2}-\frac{a_1{}^2}{B_2{}^2}\right] . \tag{48}$$

We thus infer, at the 2σ level for (47),

$$\frac{a_1{}^2}{B_1{}^2}+\frac{a_2{}^2}{B_3{}^2}-\frac{a_1{}^2}{B_2{}^2} \le 0.01 . \tag{49}$$

The term $a_1{}^2/B_2{}^2$ may be safely neglected, in view of the bound (45). Thus we find, in view of (18) and (19), that

$$B_1 \ge 260 \text{ MeV} , \tag{50}$$

$$B_3 \ge 18 \text{ GeV} . \tag{51}$$

These are more powerful than (42) and (43), but one still does better via direct experiment or (46), respectively.

The coupling strength of N_1 to muons is, according to (29b) and (30b), just the standard one times $a_1/M_{N_1} = 26$ MeV$/M_{N_1}$. This is a relatively minor suppression for $M_{N_1} \lesssim M_K$. The observed absence of $K^+\to\mu^+ N_1$ then implies[25]

$$M_{N_1} \approx B_1 \gtrsim 300 \text{ MeV}/c^2 . \tag{52}$$

The mixing parameter $|U_{\mu i}|^2$ defined in Ref. 25 is found to be $\lesssim 10^{-6}$ for $M_{N_1} \approx 300$ MeV$/c^2$. Our model would predict

$$|U_{\mu i}|^2 = (26 \text{ MeV}/300 \text{ MeV})^2 \times (3)^{\pm 2} \ge 8\times 10^{-4}$$

for this mass. The experiment of Ref. 25 does not have acceptance for N_1 masses much above 300 MeV$/c^2$, and its limits on $|U_{\mu i}|^2$ deteriorate rapidly. Gronau (last of Refs. 5) has shown how the absence of neutral decaying particles in neutrino beams can improve this limit to $M_K - m_\mu \approx 0.37$ GeV.

D. Summary

In summary, we have

$$M_{N_1} \gtrsim 0.37 \text{ GeV} , \tag{53}$$

$$M_{N_2} \gtrsim 5.8 \text{ GeV}(\times 3^{\pm 1}) , \tag{54}$$

$$M_{N_3} \gtrsim 25 \text{ GeV}(\times 3^{\pm 1}) . \tag{55}$$

It may be possible to improve (53) further, as we shall see in the next section.

IV. CONSEQUENCES OF MIXINGS

A. Lifetimes and branching ratios

The ratio of neutral- to charged-current decays is the same for each N_i of a fixed mass. It is governed only by the open channels. For example, a neutral lepton of mass 370 MeV could decay via the charged current to $\mu^- e^+ \nu_e$, $\mu^-\mu^+\nu_\mu$, and $\mu^- u\bar{d}$ (in the form of $\mu^-\pi^+$), and through the neutral current to $\nu_\mu\nu_e\bar{\nu}_e$, $\nu_\mu\nu_\mu\bar{\nu}_\mu$, $\nu_\mu\nu_\tau\bar{\nu}_\tau$, $\nu_\mu e^+ e^-$, $\nu_\mu\mu^+\mu^-$, $\nu_\mu u\bar{u}$, and $\nu_\mu d\bar{d}$ (the last two in the form of $\nu_\mu\pi^0$). There are some subtleties here. In the $\nu_\mu\nu_\mu\bar{\nu}_\mu$ channel one must take account of identical particles; the resulting rate is enhanced by a factor of 2 with respect to, e.g., $\nu_\mu\nu_e\bar{\nu}_e$. In the $\nu_\mu\mu^+\mu^-$ channel both charged and neutral currents contribute.

We estimate the open channels crudely by assigning all channels an arbitrary weight of 0 (closed), $\frac{1}{2}$ (masses important), or 1 (masses unimportant). The resulting calculated lifetime for N_1 is shown in Fig. 1 as a function of mass. A rough fit to the curve is

$$\tau_{N_1} \approx (8\times 10^{-9} \text{ sec})(M_{N_1}/1 \text{ GeV})^{-3.3} . \tag{56}$$

The additional -0.3 in the exponent reflects the opening up of new decay channels.

The corresponding lifetimes for N_2 are a factor $a_2{}^2/a_1{}^2 \approx 5000$ shorter, and for N_3 a factor of $a_3{}^2/a_1{}^2 \approx 10^5$ shorter. The N_1 particle can travel an appreciable distance before decaying as a result of the suppression of its small coupling strength by 26 MeV$/M_{N_1}$ in comparison with ordinary weak charged- and neutral-current couplings. Since all mass parameters are to be thought of as uncertain by a factor of 3, we regard these lifetime estimates as uncertain by a factor of 10. The predicted lifetimes of N_1, N_2, and N_3 are all safely within cosmological limits for neutral heavy leptons.[26] The $\mu^- u\bar{d}$ channel remains important up to quite

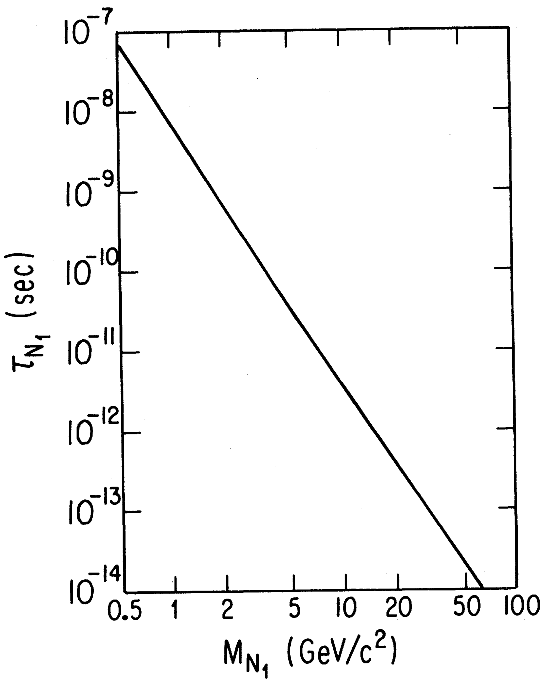

FIG. 1. Lifetime estimate for heavy lepton N_1, as a function of mass. This estimate should be considered uncertain to a factor of 10.

high masses. For a 1-GeV object, it corresponds to roughly $\frac{1}{3}$ of all decays, while it accounts for about $\frac{1}{4}$ of them at high N masses. The estimates for low N_1 masses are crude and could be improved straightforwardly. For a light N_1, the decays

$$\begin{aligned} N_1 &\to \mu^-\pi^+ \\ &\to \mu^-\pi^+\pi^0 \\ &\to \mu^-\pi^+\pi^+\pi^- \end{aligned} \tag{57}$$

are all worth searching for.[27] A heavier N_1 (above $\sim$2.5 GeV) can also decay to $\mu^- c\bar{s}$, with rate more or less equal to that for $\mu^- u\bar{d}$. Hence it may also be promising to search for $\mu^\mp F^\pm$ resonances.

B. Neutral-current production

The rates for processes ν_i + hadron$\to N_j$+(hadron)′ are given very simply in terms of ordinary neutral-current processes by (the hadrons will be omitted)

$$\frac{d\sigma(\nu_\mu\to N_1)}{d\sigma(\nu_\mu\to\nu_\mu)} = \left[\frac{26\text{ MeV}}{M_{N_1}}\right]^2 \times (\text{threshold factor}) , \tag{58}$$

$$\frac{d\sigma(\nu_\mu\to N_3)}{d\sigma(\nu_\mu\to\nu_\mu)} = \left[\frac{1.8\text{ GeV}}{M_{N_3}}\right]^2 \times (\text{threshold factor}) , \tag{59}$$

$$\frac{d\sigma(\nu_\tau\to N_2)}{d\sigma(\nu_\tau\to\nu_\tau)} = \left[\frac{1.8\text{ GeV}}{M_{N_2}}\right]^2 \times (\text{threshold factor}) , \tag{60}$$

$$\frac{d\sigma(\nu_\tau\to N_3)}{d\sigma(\nu_\tau\to\nu_\tau)} = \left[\frac{8\text{ GeV}}{M_{N_3}}\right]^2 \times (\text{threshold factor}) . \tag{61}$$

The ratios in (58)—(61) are bounded from above by $\approx$1%, 0.5%, 10%, and 10%, respectively. Each reaction has its characteristic feature.

(1) $\nu_\mu\to N_1$: The N_1 can decay to μ^-+ (any products of a charged current)$^+$. If it decays to $\mu^-\mu^+\nu_\mu$, the μ^+ can sometimes be fast, and the μ^- can be missed, giving the appearance of a wrong-sign muon event. The N_1 may travel very far if it is light, simulating an ordinary neutral-current event.

(2) $\nu_\mu\to N_3$: The N_3 prefers to decay to τ^-. This process could look like a $\nu_\mu\to\nu_\tau$ oscillation. Limits on such oscillations exist, but they are not tight enough to rule out the process (59) at the $\frac{1}{2}$% level.[28]

(3) $\nu_\tau\to N_2,N_3$: If a ν_τ beam is ever produced, these will be interesting processes to look for. (The 10% upper bound expected with respect to $\nu_\tau\to\nu_\tau$ is that associated with the expected precision in measuring the τ lifetime.)

C. *W* and *Z* decays

The W^+ can decay to various pairs with the following rates in units where $\Gamma(W^+\to e^+\nu_e)\equiv 1$:

$$W^+\to\mu^+N_1:\quad \left[\frac{26\text{ MeV}}{M_{N_1}}\right]^2 \lesssim 1\% \tag{62}$$

$$\to\mu^+N_3:\quad \left[\frac{1.8\text{ GeV}}{M_{N_3}}\right]^2 \lesssim 0.5\% \tag{63}$$

$$\to\tau^+N_2:\quad \left[\frac{1.8\text{ GeV}}{M_{N_2}}\right]^2 \lesssim 10\% \tag{64}$$

$$\to\tau^+N_3:\quad \left[\frac{8\text{ GeV}}{M_{N_3}}\right]^2 \lesssim 10\% . \tag{65}$$

Similarly, the Z decays to pairs with the following rates in units where $\Gamma(Z^0\to\nu_e\bar{\nu}_e)\equiv 1$:

$$Z^0\to\bar{\nu}_\mu N_1+\text{c.c.}:\quad 2\left[\frac{26\text{ MeV}}{M_{N_1}}\right]^2 \lesssim 2\% \tag{66}$$

$$\to\bar{\nu}_\mu N_3+\text{c.c.}:\quad 2\left[\frac{1.8\text{ GeV}}{M_{N_3}}\right]^2 \lesssim 1\% \tag{67}$$

$$\to\bar{\nu}_\tau N_2+\text{c.c.}:\quad 2\left[\frac{1.8\text{ GeV}}{M_{N_2}}\right]^2 \lesssim 20\% \tag{68}$$

$$\to\bar{\nu}_\tau N_3+\text{c.c.}:\quad 2\left[\frac{8\text{ GeV}}{M_{N_3}}\right]^2 \lesssim 20\% . \tag{69}$$

The Z decays are particularly promising sources of neutral heavy leptons because they are likely to be studied at fixed c.m. energies (at SLC and LEP).

D. Production in heavy-*Z* decays

If there exists a relatively light boson "Z_2" coupled to the U(1) in SO(10)$\to$SU(5)$\times$U(1), it will decay with an appreciable branching ratio to $N_i\bar{N}_i$. To see this, we note that the U(1) charges Q_χ of 16-plet members are, in arbitrary units,

$$5^*:\ Q_\chi=3\ ,$$
$$10:\ Q_\chi=-1\ ,\qquad (70)$$
$$1:\ Q_\chi=-5\ .$$

The branching ratio of Z_2 to $N_i\bar{N}_i$ (summed over i) is then

$$\sum_{i=1}^{3} B(Z_2\to N_i\bar{N}_i)=\frac{5^2}{5(3)^2+10(1)^2+5^2}$$
$$=\tfrac{25}{80}\approx 0.3\ .\qquad (71)$$

E. Other massive weak currents

Decays which can be studied to search for N_1 also include

$$\tau^+\to\bar{\nu}_\tau N_1\mu^+\ \ (\text{or c.c.})\ ,\quad N_1\searrow\mu^-\pi^+\qquad (72)$$

$$D^{+,0}\to\begin{Bmatrix}\bar{K}^0\\ K^-\end{Bmatrix}N_1\mu^+\ \ (\text{or c.c.})\ ,\quad N_1\searrow\mu^-\pi^+\qquad (73)$$

$$F^+\to N_1\mu^+\ \ (\text{or c.c.})\ ,\quad N_1\searrow\mu^-\pi^+\qquad (74)$$

$$\bar{b}\to\bar{c}N_1\mu^+\ \ (\text{or c.c.})\ .\quad N_1\searrow\mu^-\pi^+\ \text{or}\ \mu^-F^+\qquad (75)$$

Each of these processes is expected at a level of no more than a percent of the ordinary charged weak current. We are not aware of searches at this level of accuracy. We stress that in the present model it is really muons, and not electrons, that should appear in the final state.

As stressed by Gronau in Ref. 5, the charmed particles in (73) and (74) may give rise to the leptons N_1 in beam-dump experiments. If sufficiently long lived, these leptons N_1 may decay a considerable distance downstream from their point of production.[29,30] It has been suggested[31] that the process

$$\nu_\mu+(\text{hadronic target})\to\mu^-+F^++\cdots\ ,$$
$$F^+\to N+\mu^+\ ,$$
$$N\to\mu^-+\cdots\ ,$$

could give rise to trimuon events which were the source of some interest a while ago.[32] Similarly, some of the dimuon events, most of which were an initial signal for charm, could be due to a neutral lepton N_1 produced in neutrino interactions.

V. DECAYS $\mu\to e\gamma$ AND RELATED PROCESSES

In principle the existence of massive neutral leptons coupled to e, μ, and τ via nondiagonal couplings can induce lepton-flavor-changing radiative decays through diagrams such as that shown in Fig. 2.

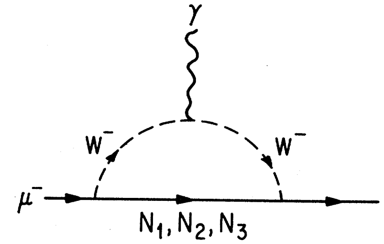

FIG. 2. Example of graph leading to $\mu^-\to e^-\gamma$.

The mixings noted in Sec. II and the corresponding couplings in Sec. III do not induce decays $\mu\to e\gamma$, but since both τ and e couple to N_2 the decay $\tau\to e\gamma$ can proceed via an N_2 intermediate state. Similarly, since both τ and μ couple to N_3, the decay $\tau\to\mu\gamma$ can proceed via an N_3 intermediate state.

The form of the rate one obtains from considering diagrams such as that shown in Fig. 2 is[33]

$$\frac{\Gamma(l_i^-\to l_j^-+\gamma)}{\Gamma(l_i^-\to\nu_i e\bar{\nu}_e)}=\frac{3}{32}\frac{\alpha}{\pi}M_W^{-4}\left[\sum_k U_{ik}U_{jk}^*{M_{N_k}}^2\right]^2\ ,\qquad (76)$$

where U_{ik} describes the mixing of the ith lepton flavor with the state N_k. As we see, all the U_{ik} are inversely proportional to M_{N_k}, so that the predicted rates are independent of M_{N_k}. Thus, we find

$$U_{\tau N_2}U_{eN_2}{M_{N_2}}^2\approx a_1a_2\approx 0.05\ \text{GeV}^2\ ,\qquad (77)$$

$$U_{\tau N_3}U_{\mu N_3}{M_{N_3}}^2\approx a_2a_3\approx 14\ \text{GeV}^2\ ,\qquad (78)$$

so

$$B(\tau\to e\gamma)\approx 1.8\times10^{-15}\ ,\qquad (79)$$

$$B(\tau\to\mu\gamma)\approx 1.4\times10^{-10}\ .\qquad (80)$$

A more careful treatment takes account of a small rotation of the charged-lepton weak eigenstates with respect to mass eigenstates.[34] The μ and e now can couple to the same neutral leptons N_i, but with further suppression factors in couplings of order $(m_{l_i}/m_{l_j})^{1/2}$ in addition to those already mentioned. (Here $m_{l_i}<m_{l_j}$.) The results are[34]

$$B(\mu\to e\gamma)\approx 8\times10^{-17}\ ,\qquad (81)$$

$$B(\tau\to e\gamma)\approx 4\times10^{-15}\ ,\qquad (82)$$

$$B(\tau\to\mu\gamma)\approx 3\times10^{-12}\ .\qquad (83)$$

These limits are all safely below present experimental bounds[16,35]

$$B(\mu\to e\gamma)\le 1.9\times10^{-10}\ ,\qquad (84)$$

$$B(\tau\to e\gamma)\le 6.4\times10^{-4}\ ,\qquad (85)$$

$$B(\tau\to\mu\gamma)\le 5.5\times10^{-4}\ .\qquad (86)$$

VI. CONCLUSIONS

The neutral massive leptons expected in SO(10) have been studied in a model which permits neutrinos to be massless. As long as there is a symmetry (discrete or global) that guarantees the form of M^N, the massless neutrinos remain massless to all orders of perturbation theory. The neutral massive objects acquire Dirac masses by combining with SO(10)-singlet fermions introduced for the purpose.

The mixing of the neutral massive leptons with ordinary neutrinos can introduce violations of weak universality. Because these violations are necessarily small, lower bounds can be placed on the masses of the neutral leptons N_1, N_2, N_3 associated with each generation of quarks and leptons.

The lower bound for N_1 we find is so weak that it may be replaced by a bound based on the absence of N_1 in $K^+ \to \mu^+ N_1$:

$$M_{N_1} \gtrsim 0.37 \text{ GeV}.^{29,36} \tag{87}$$

The corresponding bounds for N_2 and N_3 are

$$M_{N_2} \gtrsim 6 \text{ GeV} , \tag{88}$$

$$M_{N_3} \gtrsim 25 \text{ GeV} . \tag{89}$$

The leptons N_i couple to charged and neutral currents with ordinary weak strengths, multiplied by suppression factors associated with their mixings. Effectively, each N_i may be thought of as having some admixture of neutrinos. These admixtures are model-specific. We find here

$$N_1 \sim \nu_\mu \left[\frac{26 \text{ MeV}}{M_{N_1}} \right] , \tag{90}$$

$$N_2 \sim \nu_\tau \left[\frac{1.8 \text{ GeV}}{M_{N_2}} \right] , \tag{91}$$

$$N_3 \sim \nu_\mu \left[\frac{1.8 \text{ GeV}}{M_{N_3}} \right] + \nu_\tau \left[\frac{8 \text{ GeV}}{M_{N_3}} \right] . \tag{92}$$

Thus, for example, N_1 decays to $\mu + \cdots$ via the weak charged current and to $\nu_\mu + \cdots$ via the weak neutral current with a rate proportional to

$$(G_F{}^2/192\pi^3) M_{N_1}{}^5 (26 \text{ MeV}/M_{N_1})^2 \times (\text{effective number of open channels}) .$$

The lifetimes of N_1, N_2, and N_3 are then estimated crudely to be

$$\tau_{N_1} \approx (8\times 10^{-(9\pm 1)} \text{ sec})(M_{N_1}/1 \text{ GeV})^{-3.3} , \tag{93}$$

$$\tau_{N_2} \approx (8\times 10^{-(15\pm 1)} \text{ sec})(M_{N_2}/5 \text{ GeV})^{-3.3} , \tag{94}$$

$$\tau_{N_3} \approx (2\times 10^{-(18\pm 1)} \text{ sec})(M_{N_3}/25 \text{ GeV})^{-3.3} . \tag{95}$$

The N_1 lifetime is long enough that one should see visible decays, e.g., to $\mu\pi$ if the mass is sufficiently low, and to μF (for higher masses).

The prospects for observing the neutral massive leptons N_i in neutrino neutral-current interactions, in W and Z decays, and in τ, c, and b decays have been discussed. All rates involving N_1 are expected to be no more than a percent of ordinary weak rates, as a result of universality constraints in muon decay and $\pi \to l\nu$ at the percent level. The upper bounds on processes involving N_2 and N_3 are at a level of 10% of weak rates, assuming that weak universality in τ decays can be checked to the 10% level. The measurement of the τ lifetime to the best possible accuracy is of great importance.

We were motivated to construct models with light N_i in part by the existence of symmetry-breaking schemes $SO(10) \to SU(5) \times U(1)$ in which the gauge bosons Z_2 coupled to the U(1) are also relatively light. We have estimated that $B(Z_2 \to N_i \bar{N}_i) \approx 30\%$ (summed over i). Thus, *if* heavy Z's are found, we urge that neutral massive leptons be looked for in their decays. The decay $Z_2 \to N_1 \bar{N}_1$ could have a particularly spectacular signature in view of the expected long lifetime (93) of N_1.

We have checked that processes $\mu \to e\gamma$, $\tau \to e\gamma$, and $\tau \to \mu\gamma$ are predicted to occur at rates safely below present limits. For example, we expect $B(\mu \to e\gamma) \lesssim 8\times 10^{-17}$, with the precise number dependent on such unknowns as the t-quark mass and the degree to which weak universality holds in τ decays.

To sum up, we have indicated that the massive neutral leptons expected in SO(10) can be relatively light (0.37 GeV or more) if they are produced at rates only a percent or less of ordinary weak rates. We eagerly await experiments which can improve these bounds.

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