Charged leptons with nanosecond lifetimes

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Some extensions of the standard model contain additional leptons which are vectorlike under weak isospin. A class of models is considered in which these leptons do not appreciably mix with the known leptons. In such models, the heavy charged lepton and the heavy neutrino are degenerate in mass, and the degeneracy is broken by radiative corrections. The mass splitting is calculated and found to be very weakly dependent on the lepton mass, varying from 250 to 330 MeV as the mass varies from 100 to 800 GeV. This result is *not* affected significantly by inclusion in a supersymmetric model in spite of the additional loops involving the superpartners. As a result, this fairly general class of models has a charged lepton whose lifetime varies in the narrow range from 0.5 to 2.0 nsec, and which decays into neutrals plus a very low energy electron or muon.

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The relatively recent discovery that only three light neutrinos exist has constrained possible extensions of the standard model. It is no longer possible to add a fourth sequential lepton family (with a massless neutrino) to the model. Extensions which do add another generation of fermions tend to fall into one of three types: (a) sequential fermions with a right-handed neutrino, (b) mirror fermions, popular in left-right symmetric models, and (c) vectorlike fermions. Vectorlike fermions are an essential ingredient in the aspon model [1], which gauges the Peccei-Quinn symmetry to solve the strong CP problem, and vectorlike leptons appear in superstring-inspired E_6 models [2].

Although the phenomenology of all of the various types of heavy fermions has been extensively studied [3], in this Brief Report I will note a feature present in some models with vectorlike fermions that has not (to my knowledge) been discussed, and which will have some precise and unusual phenomenological implications. The focus will be on the leptonic sector, although comments will briefly be made on the extension to the quark sector. The specific models under consideration will be those in which the vectorlike leptons do not appreciably mix with the lighter leptons. The suppression of such mixing can easily be arranged via conservation of e, μ, and τ number, which can be imposed via a discrete symmetry. Alternatively, one can suppose that any mixing that does exist comes from the neutrino sector, and thus the mixing angle would be of the order of the ν_τ mass to the vectorlike neutrino mass, which (using the cosmological bound on the τ neutrino mass) must be less than 10^{-10} [4].

In such models, the vectorlike leptons $\binom{N}{L}_L$ and $\binom{N}{L}_R$ have no couplings to Higgs doublets, and are degenerate in mass. This degeneracy will be split by radiative corrections. The mass splitting will be calculated here, and the "unusual" feature is that the mass splitting is extremely insensitive to the lepton mass, and thus the lifetime of the L will be in the very narrow range of $0.5 - 2.0$ nsec, which is certainly phenomenologically interesting. Even if one extends the model to include supersymmetry (which generally can significantly change radiative corrections), this mass splitting and lifetime are *not* significantly changed. The splitting and lifetime will be calculated, and the phenomenological implications discussed.

In the simplest case, the L and N are degenerate in mass at tree level, with mass M, and this degeneracy is broken by the radiative corrections shown in Fig. 1. Contributions from charged vector bosons will cancel in the mass difference. The mass splitting is easily calculated to be

$$\Delta M \equiv M_L - M_N = \frac{\alpha M}{2\pi}\int_0^1 dx\,(1+x)\left[\ln\left(x^2+\frac{m_Z^2}{M^2}(1-x)\right) - \ln(x^2)\right].$$

Note that this expression will vanish in the limit as $m_Z \to 0$. This is expected, since in that limit the SU(2) gauge symmetry is unbroken and the L-N mass degeneracy is thus unbroken. This fact is crucial, and is responsible for the relatively mild M dependence of the mass splitting. The charged lepton L is always heavier (this is reassuring since new heavy charged stable parti-

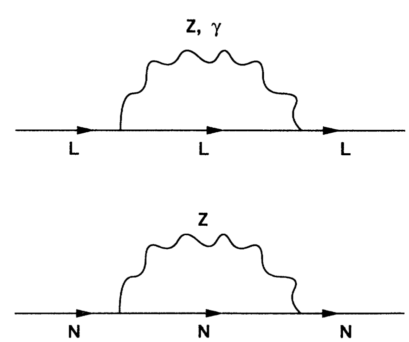

FIG. 1. Contributions to the mass splitting of a vectorlike lepton doublet. The masses of the L and N are degenerate at tree level.

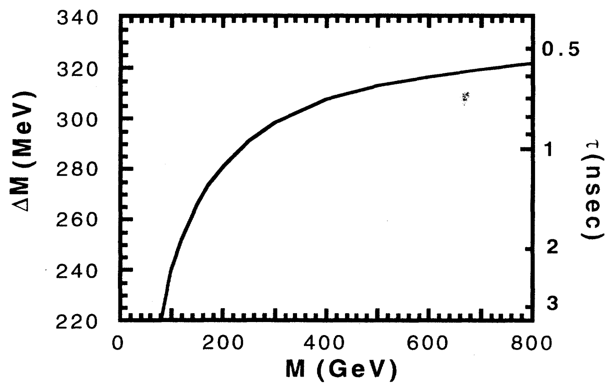

FIG. 2. The mass splitting of a vectorlike doublet, in MeV, as a function of the lepton doublet mass. The lifetime is also given in nsec.

cles are cosmologically excluded), and the above expression is plotted as a function of M in Fig. 2.

The L will decay via $L \to Ne\overline{\nu}$, $L \to N\mu\overline{\nu}$ (decays into pions, possible for the heavier masses, will be phase-space suppressed). The decay width into $Ne\overline{\nu}$ is given by (note that the coupling to the W is vectorlike)

$$\Gamma = \frac{g^2(\Delta M)^5}{960\pi^3 m_W^4} ,$$

where g is the electroweak coupling. The decay into $N\mu\overline{\nu}$ will have an identical width with a mild phase-space suppression. The total lifetime is plotted as well in Fig. 2.

The lifetime of $0.5 - 2.0$ nsec is very interesting phenomenologically. One would see a charged particle travel about a meter, then decay into a low energy (a few hundred MeV) electron or muon plus missing energy. Such a signal should have a relatively low background and may allow detection of such a lepton up to much higher masses than conventional sequential leptons (for which backgrounds, in a hadron collider, are serious problems). For vectorlike quarks, the results are identical, with an additional factor of 1/3 due to the quark charges. This leads to lifetimes of $2.5 - 10$ μsec, thus only a fraction of a percent or so will decay (through $U \to De\overline{\nu}$) in the detector. Still, the higher production rate at a hadron collider makes the detection quite likely (for example, the Fermilab Tevatron has published limits on "stable" quarks, but not "stable" leptons [5]).

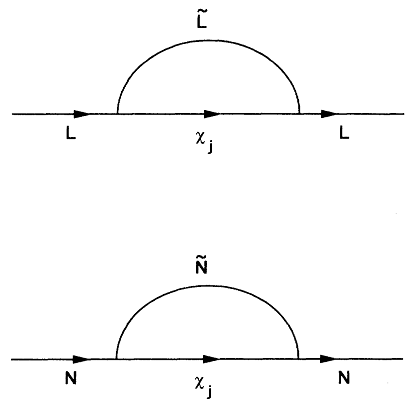

FIG. 3. Contributions to the mass splitting in a supersymmetric model. $\tilde{L}$ and $\tilde{N}$ are the scalar partners of the L and N, and are also degenerate in mass at tree level; χ_j is the neutralino ($j = 1, 4$).

How model dependent is this result? The only assumption has been the existence of vectorlike leptons which do not appreciably mix with the lighter leptons. If one adds additional Higgs doublets and singlets, the result will not change. Adding additional vectorlike leptons will also not change the result, nor will adding additional gauge groups (as long as the left- and right-handed doublets transform identically under these groups). The most popular extension of the standard model is supersymmetry; we now consider the mass splitting in supersymmetric models.

In supersymmetric models, one must also consider the diagrams of Fig. 3, in which the $\tilde{L}$ and $\tilde{N}$ are the superpartners of the L and N, and where χ_j are the neutralinos (as with the W's, charginos will not contribute in the mass difference). Although the L and N do not couple to Higgs fields, they could couple to Higgsinos due to gaugino-Higgsino mixing, and thus all four neutralinos must be considered. The Feynman rules can be extracted from the work of Haber and Kane [6]. For example, the vertex in which an L goes into a $\tilde{L}_L$ and a χ_j is given by $-i\frac{g}{\sqrt{2}}\sec\theta_W(1-\gamma_5)(-\frac{1}{2}+\sin^2\theta_W)N_{j2}+i\frac{e}{\sqrt{2}}(1-\gamma_5)N_{j1}$, where N is the matrix which diagonalizes the neutralino mass matrix. Care must be taken to use Majorana fermion propagators for the neutralinos.

The resulting mass splitting is given by

$$\frac{\alpha}{2\pi}M\sum_j A_j\int_0^1 dx\ (1-x)\ln[\tilde{m}_L^2(1-x)+m_{\chi_j}^2 x - M^2x(1-x)],$$

where

$$A_j \equiv \left[|N_{j1}|^2 - |N_{j2}|^2 + \cot\ 2\theta_w(N_{j2}^*N_{j1}+N_{j1}^*N_{j2})\right]$$

and N diagonalizes the mass matrix

$$\begin{pmatrix} M_2\sin^2\theta_w + M_1\cos^2\theta_w & (M_2-M_1)\cos\theta_w\sin\theta_w & 0 & 0 \\ (M_2-M_1)\cos\theta_w\sin\theta_w & M_2\cos^2\theta_w + M_1\sin^2\theta_w & m_Z & 0 \\ 0 & m_Z & \mu\sin 2\beta & \mu\cos 2\beta \\ 0 & 0 & \mu\cos 2\beta & -\mu\sin 2\beta \end{pmatrix}.$$

Here, $M_1 = \frac{5}{3}\tan^2\theta_w M_2$, M_2 is the SU(2) gaugino mass parameter, μ is the supersymmetric mass parameter, and $\tan\beta$ is the ratio of vacuum expectation values.

Note that the divergences in the diagrams can be obtained by replacing the integral with a $\frac{1}{\epsilon}$, and they cancel since $|N_{j1}|^2 = |N_{j2}|^2 = 1$ for a unitary matrix and the individual columns are orthogonal. It is interesting to see how the above result vanishes in the limit that $m_Z \to 0$, as it must. In that case, the mass matrix divides into two 2×2 matrices, and only the $j = 1, 2$ terms contribute. The upper 2×2 matrix can be trivially diagonalized—the mixing angle is given by the negative of the Weinberg angle. Thus, $N_{11} = N_{22} = \cos\theta_w$ and $N_{21} = -N_{12} = \sin\theta_w$. Plugging into the above, for *each* term in the sum over j, the coefficient of the integral vanishes.

Thus, the result has the expected properties, yet it appears to depend on several unknown parameters. However, it turns out that, for reasonable values of these parameters, the numerical contribution is extremely small. To see why, consider the limit of the result when $m_Z^2 \ll |M_2 - \mu|^2$, which is the case for much of the parameter space. In this case, one can use standard quantum mechanical time-independent perturbation theory; the small expansion parameter is $\lambda \equiv \frac{m_Z \cos\phi \cos\theta_w}{M_2 - \mu}$ where $\phi \equiv \frac{\pi}{4} - \beta$. The correction to the $m_Z \to 0$ limit to first order in λ vanishes; the second order correction arises from the normalization of the first order "wave functions." The coefficient of the integral in the above expression (for $j = 1$, for example) becomes

$$\cos^2\theta_w - \frac{\sin^2\theta_w}{1+\lambda^2} - 2\cot\ 2\theta_w \frac{\cos\ \theta_w \sin\theta_w}{\sqrt{1+\lambda^2}}.$$

Expanding this out to leading order in λ^2 gives $2\lambda^2(\sin^2\theta_w - \frac{1}{4})$. A similar expression occurs for the other terms in the sum. The appearance of the $\sin^2\theta_w - \frac{1}{4}$ factor (which appears unrelated to the vector coupling of leptons to the Z in the standard model) makes the final contribution at most a few MeV, and thus negligible.

Thus, the result that vectorlike leptons that do not mix appreciably with lighter leptons have a lifetime between 0.5 and 2.0 nsec is very robust, and is not affected even by the addition of supersymmetry. The generality of such models is sufficient that experimenters searching for exotic leptons are encouraged to pay particular attention to charged leptons with lifetimes of about a nanosecond and which decay into neutrals plus a low energy electron and/or muon.

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