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Production, collection, and utilization of very long-lived heavy charged leptons

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If a fourth generation of leptons exists, both the neutrino and its charged partner must be heavier than 45 GeV. We suppose that the neutrino is the heavier of the two, and that a global or discrete symmetry prohibits intergenerational mixing. In that case, nonrenormalizable Planck scale interactions will induce a very small mixing; dimension-five interactions will lead to a lifetime for the heavy charged lepton $\sim (1-100)$ yr. Production of such particles is discussed, and it is shown that a few thousand can be produced and collected at a linear collider. The possible uses of these heavy leptons are also briefly discussed.

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It has now been established [1] at the CERN e^+e^- collider LEP that there are three light neutrinos. If a fourth generation exists, the mass of both its neutrino N and the associated charged lepton L must exceed 45 GeV or it would have been observed at LEP. Such a generation would be unique in that the neutrino and charged lepton will have masses which do not differ by much more than an order of magnitude [2].

In this Brief Report, we consider the implications of a fourth generation with the following two properties: (a) the mass of the neutrino is greater than the mass of the charged lepton and (b) some symmetry (discrete or global), which remains unbroken as electroweak symmetry breaking takes place, prevents intergenerational mixing (in the lepton sector). Neither of these assumptions is particularly implausible. The first simply chooses a particular half of the allowed parameter space. The second is just an extension of the familiar electron-number, muon-number and τ-number conservation laws.

As a consequence of these two properties, the charged lepton L would appear to be absolutely stable. This is a cosmological disaster. The abundance of these leptons today would be large enough that they could not have escaped detection in terrestrial experiments (searches for heavy hydrogen in water). A detailed analysis of the cosmological bounds can be found in Ref. [3], where an upper bound of roughly 100 years is found on the lifetime of a charged lepton. For lifetimes greater than 100 years, the photons emitted in the decay would distort the microwave background radiation more than is observed by the Cosmic Background Explorer (COBE).

The model is not necessarily excluded, however. It has long been recognized that black holes violate global and discrete symmetries [4], and one would expect quantum gravitational effects to also violate such symmetries (a discrete gauge symmetry [5], however, remains unspoiled by such effects). Thus, higher-dimensional operators, scaled by the Planck mass, which violate such symmetries cannot be excluded. In the case of baryon number conservation, dimension-six operators will lead to proton decay with a lifetime of $\sim (10^{45})$ yr. More recently, it has been realized [6] that axion models are ruled out if, as one expects, quantum gravitational effects do not respect the Peccei-Quinn symmetry. In our case, one would expect higher-dimensional operators to violate the symmetry which prevents intergenerational mixing, leading to a finite, albeit very long, lifetime for the L. We will not address here the origin of the symmetries responsible for L being nearly stable.

How long does one expect the lifetime to be? If the mixing angle is θ, then the decay rate is $G_F m_L^3 \sin^2\theta/(8\pi\sqrt{2})$, or approximately $10^{24}\sin^2\theta$ sec^{-1} for a lepton of mass 200 GeV. If the lowest-dimension Planck scale operator which violates the symmetry is dimension six (or higher), then the mixing angle will be smaller than $M_W^2/M_{\rm Pl}^2$, leading to a lifetime in excess of 10^{37} years, which is cosmologically unacceptable. However, if a dimension five operator violates the symmetry, then the mixing angle will be $O(M_W/M_{\rm Pl})$, leading to a lifetime of approximately 1–100 years, close to the cosmological bound.

Two models will illustrate this point. Suppose the L has a mass of 250 GeV, and consider mixing between the L and the τ. In one model, one can introduce a gauge singlet scalar[1] S and write a dimension five operator:

$$\frac{f_{L\tau}}{M_{\rm Pl}}\,\bar{L}_L\Phi\tau_R\,S+\frac{f_{\tau L}}{M_{\rm Pl}}\,\bar{\tau}_L\Phi L_R\,S+\text{ H.c.},\tag{1}$$

where we have assumed that L_L is a doublet under SU(2)$_L$, Φ is the standard model Higgs boson, and $f_{L\tau}$ and $f_{\tau L}$ are constants of order 1. In another model, one

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[1] A natural choice for such a singlet in a supersymmetric model would be the fourth generation scalar neutrino; if it gets a vacuum value, then this would naturally explain why the fourth generation neutrino is heavy.

can have the L being a mirror fermion (left-handed singlet and right-handed doublet) [7], and write, in obvious notation, the dimension five operators

$$\frac{f_{L\tau}}{M_{\rm Pl}}\,\bar{L}_L\Phi^\dagger\Phi\tau_R+\frac{f_{\tau L}}{M_{\rm Pl}}\,\bar{\tau}_L\Phi\Phi^\dagger L_R+\text{ H.c.} \tag{2}$$

When Φ (and in the first model, S) acquire vacuum expectation values, mixing between the L and the τ will be induced. In the latter model, the lifetime turns out to be $\sim \frac{10}{f^2}\left(\frac{250\text{ GeV}}{m_L}\right)$ years, with f of order 1; in the former model this is multiplied by $(250\,\text{GeV}/\langle S\rangle)^2$. While we are not advocating any particular model, one can see that plausible models with a lifetime in the 1–100 year range can easily be constructed.

Such a long lifetime leads to the possibility that one could produce these particles at a high energy collider, stop them in some material, physically transport them away from the detector environment and study them at length. We now consider these possibilities.

A particle with several tens or hundreds of GeV of kinetic energy is difficult to stop, and thus one would want to produce the L's at an electron-positron collider just above threshold. In the case that the heavy fermion family has the same electroweak couplings as the lighter lepton families, the production cross section is given by

$$\frac{d\sigma}{d\cos\theta}=\frac{\beta}{32\pi s}\,[\ \xi_1\,(1+\cos^2\theta)+(1-\beta^2)\,\xi_2\,\sin^2\theta \\ +\xi_{\rm FB}\,\cos\theta\,], \tag{3}$$

where θ is the angle, in the c.m. frame, between the outgoing L^- and the incoming electron, and

$$\begin{aligned}\xi_2&=(e^2+g_Z^2)^2+a^2\ g_Z^4,\\ \xi_1&=\xi_2+\beta^2\ a^2\ g_Z^4\ \ (1+a^2),\\ \xi_{\rm FB}&=-\,8\ a^2\ \beta\ g_Z^2\ \ (g_Z^2+\tfrac{1}{2}\ e^2).\end{aligned} \tag{4}$$

Here we have defined $a\equiv 1/(4\sin^2\theta_W-1)$, $e\equiv g\sin\theta_W$, and $g_Z\equiv (g/4a)\sec\theta_W$. The result is given in the limit of $\sqrt{s}>>M_Z$; the M_Z dependence can be included by multiplying g_Z^2 by $s/(s-M_Z^2)$. The kinetic energy of the L, of course, is $\frac{1}{2}M\beta^2$. Note that in the limit of small β, the distribution is isotropic. If one has a luminosity of 3×10^{33} cm^{-2} sec^{-1} (which is the expected luminosity of the Next Linear Collider), then in a year of running the number of L's produced is approximately $7\times 10^4\beta$. In Table I, the precise number of L's produced as a function of β is given (taking the L mass to be 200 GeV), as well as the kinetic energy and stopping distance in liquid argon. We see that many thousands of sufficiently low energy L's can be produced. For definiteness, we will take $\beta=0.2$, and thus 14 500 can be produced annually.

Many properties of the L will be determined directly from production cross section. The mass can be measured precisely from the energy threshold, and the spin will be immediately determined from the angular distribution. Other quantum numbers can be determined from the forward-backward asymmetry, given by

$$A_{\rm FB}=\xi_{\rm FB}/[\tfrac{8}{3}\ \xi_1+(1-\beta^2)\ \xi_2]. \tag{5}$$

This asymmetry vanishes at $\beta=0$ and, for $\beta\le 0.6$, increases roughly linearly with a slope of ~ 0.4. For $\beta=0.2$, the asymmetry of 0.08 could be easily detected with an integrated luminosity of 10^{41} cm^{-2}; we estimate that an asymmetry of 0.01 could be measured in this case. Measurement of this asymmetry offers the possibility of determining whether L belongs to a doublet of SU$(2)_L$ by checking that the axial-vector coupling of the L to the Z is the same as that of the electron. We estimate that g_A can be measured to an accuracy of ten percent; g_V is naturally small and thus cannot be determined accurately. If the heavy lepton belongs to a mirror lepton family, all the above applies except that now the forward-backward asymmetry has the same magnitude but the opposite sign [8]. Finally, one can consider detecting a possible electric dipole moment (EDM) of the L. In many models, the EDM rises as the cube of the lepton mass, and could be very large in this case. However, by considering the effects of an EDM on the angular distribution (see Ref. [9] for a detailed expression), we can see that the above luminosity will only allow an EDM to be measured if it is greater than 2×10^{16} e cm. This value is at least an order of magnitude greater than the largest values expected theoretically [10], and thus it is unlikely to be seen.

Of greater interest, of course, is the possibility of capturing the L's. The stopping distance in liquid argon (Table I) is certainly experimentally tractable; the stopping distance in other substances will scale roughly inversely with the density, and thus will not differ greatly. The charge could be determined by observing the curvature of the track in a magnetic field (a 2 T B field will bend a lepton of mass 200 GeV with $\beta=0.2$ with a radius of curvature of 70 m); this determination is essential in obtaining the forward-backward asymmetry mentioned in the above paragraph.

L^- will most likely be captured by the highest Z nucleus in the stopping medium. The result is a heavy nucleus of charge $Z-1$. Thus, if the stopping medium were argon, the result is a chlorinelike atom. This could then be chemically separated from the inert argon. Alternatively, stopping L^- in Na or K would lead to an inert Ne- or Ar-like atom which could be boiled off and then condensed onto a collector.

The L^+ will probably pick up an electron upon stopping. Stopping in an inert gas might delay this capture process, but the lepton is unlikely to remain charged for times comparable to the collection and extraction times. For example, positive muons can be extracted with an

TABLE I. Production cross section, number of heavy leptons produced per year, kinetic energy (KE), and stopping distance in liquid Ar as a function of β for a 200 GeV heavy charged lepton.

β	0.3	0.2	0.1
σ(pb)	0.24	0.16	0.08
No./yr.	22,000	14,500	7,600
KE (GeV)	9.0	4.0	1.0
d in liquid Ar (cm.)	225	55	5

efficiency of 10^{-4} from argon in a microsecond; however, there is already evidence that electrons diffuse toward the muon in this amount of time. Thus, the L^+ will almost certainly be neutralized. The (L^+e) atom produced in this way will be chemically identical to hydrogen, and equally chemically active. Thus, for example, one could stop the (L^+e) atom in a chlorinated liquid and then it would react with the Cl to produce LCl which could then be evaporated and collected. To avoid missing half of the L's, one might wish to use the same stopping medium, such as argon, for each, in which case one would have to chemically extract the hydrogenlike atom from argon.

Since the mass, energy, and charge of the L's will be known before they enter the stopping medium, the range will be known to within a few centimeters. With a segmented stopping medium, one could isolate their location to within a volume of a few tens of milliliters. Since the production rate of Table I corresponds to roughly one event per hour, one could remove that volume and perform the chemical extraction at another site. One might even avoid chemical extraction altogether and use a mass spectrometer to isolate the L's (since their mass is known); more likely both would be used. In any event, collection of thousands of L^+'s and L^-'s should be possible.

What can one do with a few thousand L's? The first important measurement would be the lifetime and decay products (it presumably decays into a ν and a real or virtual W). The L's could be placed in an underground detector such as super-Kamiokande, and the decays could be individually measured. Since the cosmological bound on the lifetime is less than 100 years or so, the lifetime could be determined fairly rapidly.

A few thousand L's would be useless as an energy storage device ($10^4\, M_L\, c^2$ is less than a millijoule). Since the reduced mass of an (L^-p) hydrogen atom is the proton mass, the L's would catalyze D-D and D-T fusion much as does a μ^- [11]. However, the fusion rates are limited by the capture rates to L^-D and then to DL^-D, since once DL^-D is formed (or, for that matter, $D\mu^-D$), the fusion rate is essentially instantaneous. Thus L^- should catalyze fusion slower than μ^- because the greater mass of the L^- reduces the velocities upon which the capture rates are directly dependent. Even at the rate at which muons catalyze fusion, which is roughly one fusion per nanosecond, each L will produce roughly a milliwatt, and thus a few thousand would not give a practical energy source [12].

Finally, one might be able to use the L's to study nuclear structure. The x rays emitted when an L^- cascades down towards the center of a nucleus would give information about the electromagnetic structure of the nucleus [it is doubtful, however, whether more information can be obtained in this manner than by electron scattering, such as at the Continuous Electron Beam Accelerator Facility (CEBAF)]. A detailed discussion of the possible uses of heavy stable particles can be found in Ref. [13], where Zweig discusses the effects of very heavy stable quarks. He shows that large nuclei would fission upon capture of a heavy stable particle, that α decay could be facilitated upon capture of an L (for example, introducing a stable quark of mass 300 MeV and charge $-4/3$ into thorium will reduce its half-life by a factor of 10^{36}), and that a new type of molecules would be produced. Unfortunately, many of the effects he considers would require many more than a few tens of thousands of L's in order to be of practical use [12].

In this work we have considered the production, collection, and utilization of very-long-lived heavy leptons. It must be emphasized that our only assumptions are that (a) a fourth generation of fermions exists, (b) the neutrino of that generation is heavier than the charged lepton, and (c) a discrete or global symmetry prohibits intergenerational mixing. Given the first assumption, we do not believe that either of the other two is particularly unlikely. It has been shown that the lifetime can be of the order of ten years, and that thousands of these heavy leptons could be collected at an electron-positron collider with an energy slightly above threshold. Although we have speculated on the possible uses of such leptons, such speculation is undoubtedly premature–clearly there will be applications that we have not yet imagined. More important, the discovery of a heavy lepton with the properties considered here should have a deep significance for a further understanding of the generation problem.

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[2] A significant mass splitting between the neutrino and charged lepton would affect electroweak radiative corrections. The major effect would be on the "T" parameter, which would change by $3(m_L^2 - m_N^2)/(16\pi^2 \sin^2\theta_W m_W^2)$. It is impossible to bound this quantity without knowing the masses of the top and fourth generation quarks; if the former is 140 GeV and the latter are degenerate, then $m_N^2 - m_L^2$ must be less than $\sim$ (300 GeV)^2, which is a fairly mild constraint on models. The effects on the S and U parameters are only logarithmic in the mass splitting.

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