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[8] The corresponding operators are

$$\mathcal{O}_{51-52} = i\int d^4x\, \bar{\psi}\,[(iD)^2, (e/2)\sigma_{\mu\nu}F^{\mu\nu}]\psi,$$

$$\mathcal{O}_{61-65} = i\int d^4x\, \bar{\psi}\,[(iD)^2 i\not{D}, eF_{\mu\nu}\gamma^\nu D^\mu, e\gamma^\mu(\partial^\nu F_{\mu\nu}), -ieF_{\mu\nu}\sigma^{\mu\nu}\not{D}/2, F_{\mu\nu}\,\partial^2 F^{\mu\nu}/4]\psi;$$

$\mathcal{O}_{66-68}$ are four-fermion operators.

[9] It may be noted that the lowest-order contribution to electron $(g-2)/2$ is $(\alpha/\pi)^2(m/M)^2\times 1/45$ [B. E. Lautrup and E. de Rafael, Phys. Rev. 174, 1835 (1968)]. The question arises whether the next-order correction may be of order $(\alpha/\pi)^3(m/M)^2[\ln(m/M)]^2$, which is comparable to $(\alpha/\pi)^4$ and therefore should become important in view of the work in progress by T. Kinoshita. Our answer is that such effects due to muons do not exist.

Baryon- and Lepton-Nonconserving Processes

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A number of properties of possible baryon- and lepton-nonconserving processes are shown to follow under very general assumptions. Attention is drawn to the importance of measuring μ^+ polarizations and $\bar{\nu}_e/e^+$ ratios in nucleon decay as a means of discriminating among specific models.

Of the supposedly exact conservation laws of physics, two are especially questionable: the conservation of baryon number and lepton number. As far as we know, there is no necessity for an *a priori* principle of baryon and lepton conservation. As we shall see, even without such a principle, the fact that the weak, electromagnetic, and strong interactions of ordinary quarks and leptons conserve baryon and lepton number can be understood as simply a consequence of the $SU(2)\otimes U(1)$ and $SU(3)$ gauge symmetries. Also, in contrast with the conservation of charge, color, and energy and momentum, the conservation of baryon number and lepton number are almost certainly not unbroken local symmetries.[1] Not only is baryon conservation unnecessary as a fundamental principle, the apparent excess of baryons over antibaryons in our universe provides a positive clue that some sort of physical processes have actually violated baryon-number conservation.[2] Violations of baryon and lepton conservation are likely to occur in grand unified theories that combine the gauge theory of weak and electromagnetic interactions with that of strong interactions and have leptons and quarks in the same gauge multiplets, and such violations have been found in various of these models.[3]

The purpose of this paper is to point out those features of baryon- or lepton-nonconserving processes that are to be expected on very general grounds. Other features will be indicated that may be used to discriminate among specific models.

No grand unified model or other specific gauge model of baryon- and lepton-nonconserving processes will be adopted here. Instead, it will simply be assumed that these processes are mediated by some unspecified "superheavy" particles, with a characteristic mass M above, say, 10^{14} GeV. Such large masses are indicated by the experimental lower bound[4] on the proton lifetime, and are also required in order that these particles should decay sufficiently early in the history of the universe to yield an appreciable baryon number.[2] Large masses are also required by general ideas of grand unification[5]: The strong coupling g_S of quantum chromodynamics (QCD) decreases so slowly with increasing energy that we must go up to very high energies before g_S becomes comparable with the weak and electromagnetic couplings g, g'.

In addition, it will be assumed here that the only particles with masses much less than the superheavy mass scale M are the "ordinary" particles of the sort with which we are familiar: left-handed lepton and quark doublets l_{iaL} and $q_{i\alpha aL}$; right-handed lepton and quark singlets l_{aR}, $u_{\alpha aR}$, and $d_{\alpha aR}$; and color-neutral bosons $W^{\pm}$, Z^0, γ, gluons, and Higgs scalars. [Here $\alpha = 1, 2, 3$ is an SU(3) index; $i = 1, 2$ is an SU(2) index; and $a = 1, 2, 3, \ldots$ is a "generation" index, distinguishing $e, \mu, \tau, \ldots$; $u, c, t, \ldots$; $d, s, b, \ldots$.] As it stands, this is a fairly restrictive assumption, but there are many other types of particles whose presence at ordinary mass levels would not affect our conclusions. Of course, one can also give examples of possible exotic particle types, whose presence at mass levels below the superheavy mass scale M could invalidate the general rules derived below; any observed departures from these rules would then provide valuable data on the nature of such exotic particles. Most of our results do not depend in any way on the nature of the superheavy particles of mass M, but we shall also see what consequences follow from the further assumption that baryon instability is due to exchange of a single superheavy vector or scalar boson.

Physical processes which occur at ordinary energies, including proton decay, can be described in terms of an SU(3) ⊗ SU(2) ⊗ U(1)-invariant effective field theory, which is obtained by integrating out all the superheavy degrees of freedom. The effective theory involves only the "ordinary" particles whose mass is much less than the characteristic superheavy mass scale M. The ordinary bosons which appear in the effective theory all have vanishing baryon number and lepton number, so that purely bosonic terms in the effective Lagrangian conserve baryon number and lepton number trivially. Also, for interactions involving a pair of ordinary fermions and any number of derivatives and ordinary bosons, SU(3) of QCD immediately implies baryon conservation.[6] Hence the terms in the effective Lagrangian which violate baryon conservation must involve at least four fermion fields.

These operators have dimensionality (mass)^d, with $d \geq 6$. But the only mass scale entering in the determination of the effective Lagrangian is the characteristic mass M of the superheavy particles,[7] and so the effective coupling constants associated with these operators must on dimensional grounds be roughly of order M^{4-d}. With M as large as assumed here, the only baryon-nonconserving interactions of practical interest are those given by the operators with $d = 6$. These have just four fermion fields and no derivatives or boson fields.

It is straightforward to enumerate all possible operators of this type which are SU(3) ⊗ SU(2) ⊗ U(1) invariant and do not conserve baryon number:

$$O^{(1)}_{abcd} = (\bar{d}^C_{\alpha aR} u_{\beta bR})(\bar{q}^C_{i\gamma cL} l_{jdL})\epsilon_{\alpha\beta\gamma}\epsilon_{ij}, \qquad (1)$$

$$O^{(2)}_{abcd} = (\bar{q}^C_{i\alpha aL} q_{j\beta bL})(\bar{u}^C_{\gamma cR} l_{dR})\epsilon_{\alpha\beta\gamma}\epsilon_{ij}, \qquad (2)$$

$$O^{(3)}_{abcd} = (\bar{q}^C_{i\alpha aL} q_{j\beta bL})(\bar{q}^C_{k\gamma cL} l_{ldL})\epsilon_{\alpha\beta\gamma}\epsilon_{ij}\epsilon_{kl}, \qquad (3)$$

$$O^{(4)}_{abcd} = (\bar{q}^C_{i\alpha aL} q_{j\beta bL})(\bar{q}^C_{k\gamma cL} l_{ldL})\epsilon_{\alpha\beta\gamma} \times (\vec{\tau}\epsilon)_{ij} \cdot (\vec{\tau}\epsilon)_{kl}, \qquad (4)$$

$$O^{(5)}_{abcd} = (\bar{d}^C_{\alpha aR} u_{\beta bR})(\bar{u}^C_{\gamma cR} l_{dR})\epsilon_{\alpha\beta\gamma}, \qquad (5)$$

$$O^{(6)}_{abcd} = (\bar{u}^C_{\alpha aR} u_{\beta bR})(\bar{d}^C_{\gamma cR} l_{dR})\epsilon_{\alpha\beta\gamma}. \qquad (6)$$

Here α, β, and γ are SU(3) indices; i, j, k, and l are SU(2) indices; a, b, c, and d are generation indices; l_{iaL} and $q_{i\alpha aL}$ are generic left-handed lepton and quark SU(2) doublets; l_{aR}, $u_{\alpha aR}$, and $d_{\alpha aR}$, are generic right-handed charged lepton and quark SU(2) singlets; C denotes the Lorentz-invariant complex conjugate; and ϵ_{ij} and $\epsilon_{\alpha\beta\gamma}$ are the totally antisymmetric SU(2) and SU(3) tensors with $\epsilon_{12} \equiv \epsilon_{123} \equiv +1$. Fierz transformations have been used to put the various Fermi interactions in the form of Eqs. (1)–(6), and in particular, to eliminate all vector and tensor Dirac matrices.

Inspection of Eqs. (1)–(6) leads immediately to a number of general rules which govern baryon-nonconserving interactions:

(A) $\Delta L = \Delta B$.—All interactions (1)–(6) conserve the difference of the baryon number B and lepton number L. Hence nucleons can only decay into antileptons, not leptons. The conservation of $B - L$ has already been noted[8] as a general consequence of SU(3) ⊗ SU(2) ⊗ U(1) invariance in the couplings of arbitrary superheavy scalar or vector bosons to pairs of ordinary fermions, but this argument leaves open the possibility that conservation of $B - L$ could be violated in baryon decay by graphs of higher order in α, involving

$(B-L)$-nonconserving violating couplings of superheavy bosons to each other, or to superheavy fermions. The fact that (1)–(6) conserve $B-L$ implies that $(B-L)$-nonconserving processes like $n\to e^-\pi^+$ are suppressed relative to $(B-L)$-conserving processes like $n\to e^+\pi^-$ or $p\to e^+\pi^0$ by factors of order $m_W/M \lesssim 10^{-12}$, and not just by powers of α.

(B) $\Delta S/\Delta B \leqslant 0$.—The $\Delta B=\Delta L=-1$ operators (1)–(6) can contain 0, 1, or 2 fields which destroy s quarks, but no fields which create s quarks, so processes like $p\to\overline{K}^0 l^+$ or $n\to\overline{K}^- l^+$ with $\Delta S=\Delta B$ are forbidden.[9]

(C) $\Delta I = 1/2$.—Interactions with $\Delta S=0$ and $\Delta B=-1$ are obtained by replacing the generic quark fields of charge $\frac{2}{3}$ and $-\frac{1}{3}$ in Eqs. (1)–(6) with u and d, respectively. Explicitly,[10]

$$O^{(1)}_{\Delta S=0}=(\bar d^C_{\alpha R}u_{\beta R})(\bar u^C_L l_L^- - \bar d^C_{\gamma L}\nu_L)\epsilon_{\alpha\beta\gamma}, \tag{7}$$

$$O^{(2)}_{\Delta S=0}=-2(\bar d^C_{\alpha L}u_{\beta L})(\bar u^C_{\gamma R}l_R^-)\epsilon_{\alpha\beta\gamma}, \tag{8}$$

$$O^{(3)}_{\Delta S=0}=-2(\bar d^C_{\alpha L}u_{\beta L})(\bar u^C_{\gamma L}l_L^- - \bar d^C_{\gamma L}\nu_L)\epsilon_{\alpha\beta\gamma}, \tag{9}$$

$$O^{(4)}_{\Delta S=0}=O^{(6)}_{\Delta S=0}=0, \tag{10}$$

$$O^{(5)}_{\Delta S=0}=(\bar d^C_{\alpha R}u_{\beta R})(\bar u^C_{\gamma R}l_R^-)\epsilon_{\alpha\beta\gamma}. \tag{11}$$

(Here l^- is any of e,μ,τ; and ν is the corresponding neutrino.) The antisymmetric part of $\bar d^C_\alpha u_\beta$ is an isoscalar, so the operators multiplying the l_L^- and ν_L fields form isotropic doublets, and the operators multiplying the l_R^- field are the top members of other isotopic doublets. This leads directly to a number of simple relations among rates,[11] such as

$$\Gamma(p\to l_R^+\pi^0)=\tfrac{1}{2}\Gamma(n\to l_R^+\pi^-) =\tfrac{1}{2}\Gamma(p\to\bar\nu\pi^+)=\Gamma(n\to\bar\nu\pi^0) \tag{12}$$

and

$$\Gamma(p\to l_L^+\pi^0)=\tfrac{1}{2}\Gamma(n\to l_L^+\pi^-). \tag{13}$$

There are also relations among inclusive rates, such as

$$\Gamma(p\to l_R^+X)=\Gamma(n\to\bar\nu X),\quad \Gamma(n\to l_R^+X)=\Gamma(p\to\bar\nu X). \tag{14}$$

For experiments in which the charged lepton helicities are not measured, the relations (12)–(14) must be combined to give

$$\Gamma(p\to l^+\pi^0)=\tfrac{1}{2}\Gamma(n\to l^+\pi^-)\geqslant\tfrac{1}{2}\Gamma(p\to\bar\nu\pi^+); \tag{15}$$

$$\Gamma(p\to l^+X)\geqslant\Gamma(n\to\bar\nu X),\quad \Gamma(n\to l^+X)\geqslant\Gamma(p\to\bar\nu X). \tag{16}$$

(Relations connecting $\bar\nu$ and l^+ processes are only valid in the limit of relativistic l^+ velocities.)

We will now consider one further assumption. To lowest order in α, baryon nonconservation would presumably be due to exchange of a single vector or scalar superheavy boson. It has been shown[8] that in general there are just five kinds of superheavy vector or scalar bosons that can have $SU(3)\otimes SU(2)\otimes U(1)$-invariant baryon-nonconserving interactions to a pair of ordinary fermions: These are SU(3)-triplet, SU(2)-doublet vector bosons X_V, X_V' of charges $(\frac{4}{3},\frac{1}{3})$ and $(\frac{2}{3},-\frac{1}{3})$; SU(3)-triplet, SU(2)-singlet scalar bosons X_S, X_S' of charges $-\frac{1}{3}$, $-\frac{4}{3}$; and SU(3)-triplet, SU(2)-triplet scalar bosons X_S'' of charge $(\frac{2}{3},-\frac{1}{3},-\frac{4}{3})$; plus their antiparticles. It is straightforward[12] to check that X_S exchange can contribute to interactions of form $O^{(1)}$, $O^{(2)}$, $O^{(3)}$, and $O^{(5)}$; X_S' and X_S'' can contribute only to $O^{(6)}$ and $O^{(4)}$, respectively; while X_V exchange can contribute only to $O^{(1)}$ and $O^{(2)}$; and X_V' exchange only to $O^{(1)}$. If we assume that baryon nonconservation is due to exchange of any sort of *vector* boson, then only $O^{(1)}$ and $O^{(2)}$ enter, and we can write the effective Lagrangian for $\Delta S=0$ and $\Delta S=-\Delta B$ baryon-nonconserving processes as

$$\mathcal{L}=[g_1(\bar d^C_{\alpha R}u_{\beta R})(\bar u^C_{\gamma L}l_L^- - \bar d^C_{\gamma L}\nu_L)+g_2(\bar d^C_{\alpha L}u_{\beta L})(\bar u^C_{\gamma R}l_R^-) + g_1'(\bar s^C_{\alpha R}\bar u_{\beta R})(\bar u^C_{\gamma L}l_L^- - \bar d^C_{\gamma L}\nu_L)+g_1''(\bar d^C_{\alpha R}u_{\beta R})(\bar s^C_{\gamma L}\nu_L)+g_2'(\bar s^C_{\alpha L}u_{\beta L})(\bar u^C_{\gamma R}l_R^-)+\text{H.c.}]\epsilon_{\alpha\beta\gamma}. \tag{17}$$

This leads to an immediate result for charged-lepton emission.

(D) *Universal polarization.*— The hadronic operator associated with l_L^- in $\Delta S=0$ processes is just g_1/g_2 times the parity transform of the hadronic operator associated with l_R^-, and similarly for $\Delta S=1$ processes. It follows that for relativistic charged leptons, the lepton polarizations take constant values, which depend only on whether the decay mode has $\Delta S=0$ or $\Delta S=-\Delta B$:

$$P_{\Delta S=0}=\frac{|g_1|^2-|g_2|^2}{|g_1|^2+|g_2|^2},\quad P_{\Delta S=-\Delta B}=\frac{|g_1'|^2-|g_2'|^2}{|g_1'|^2+|g_2'|^2}, \tag{18}$$

where

$$P \equiv \frac{\Gamma(N \to l_R^+ H) - \Gamma(N \to l_L^+ H)}{\Gamma(N \to l_R^+ H) + \Gamma(N \to l_L^+ H)} \tag{19}$$

with H any specific hadronic channel.

An experimental check of the results (A)–(D) would be useful as a test of the general assumptions described above. In particular, verification of $\Delta I = \frac{1}{2}$ relations like (12)–(16) would provide a good indication that baryon nonconservation is due to virtual particles so heavy that $SU(2)\otimes U(1)$ is effectively unbroken in their interactions. Also, verification of the universality of the charged-lepton polarizations would indicate an absence of significant scalar-boson exchange; the inclusion of operators $O^{(3)}$, $O^{(5)}$ which could be produced by X_S exchange would lead to lepton polarizations which depend on the relative values of matrix elements of $(\bar{d}_{\alpha R}^C u_{\beta R}) u_{\gamma L} \epsilon_{\alpha\beta\gamma}$ and $(\bar{d}_{\alpha L}^C u_{\beta L}) u_{\gamma L} \epsilon_{\alpha\beta\gamma}$, and hence which depend on the details of the decay mode. But a check of (A)–(D) cannot be used to verify any specific gauge model of baryon decay.

Within the context described here, different models of baryon nonconservation can be distinguished only through measurements of the five parameters $g_1, g_2, g_1', g_1'', g_2'$ for each lepton type. But as already mentioned above, as far as charged leptons are concerned, the operators multiplying g_1 and g_2 in Eq. (17) are simply space inversions of each other, and likewise for g_1' and g_2', and so if parity-odd operators are not measured, the only quantities that can be determined in observations of charged lepton modes are the overall coupling scales $|g_1|^2 + |g_2|^2$ and $|g_1'|^2 + |g_2'|^2$. Under our general assumptions, for $\Delta S = 0$ and $\Delta S = \Delta B$ baryon-nonconserving charged-lepton processes, as long as no pseudoscalars are measured, *all models must give the same results for the relative rates of different decay modes*, and can differ only in the total $\Delta S = 0$ and $\Delta S = \Delta B$ decay rates for each lepton type.

This conclusion serves to emphasize the importance of measuring charged lepton polarizations or $\bar{\nu}/l^+$ ratios in nucleon decay. Different models will give quite different polarizations: For instance, if X_V' exchange is dominant then $g_2 = g_2' = 0$, so that $P = +1$ in both $\Delta S = 0$ and $\Delta S = -\Delta B$ processes, while if X_V exchange is significant then P will depend on ΔS and on the details of the model.

Fortunately, if baryon nonconservation is discovered, it should be feasible to determine the lepton polarization, perhaps in a second round of experiments. The μ^+ polarization can be determined from the direction of positrons from stopped muons, using the same detection system that is used to detect positrons from nucleon decay. The e^+ polarization would probably have to be determined indirectly, using the $\Delta I = \frac{1}{2}$ relations (12) or (14). Once these polarizations are measured, Eq. (18) can be used to discriminate among models, with no need to worry about complications due to strong interactions.

The sort of analysis used here in treating baryon nonconservation can also be applied to lepton nonconservation. A great difference is that there is a possible lepton-nonconserving term in the effective Lagrangian with dimensionality $d = 5$:

$$f_{abmn} \bar{l}_{iaL}^C l_{jbL} \varphi_k^{(m)} \varphi_l^{(n)} \epsilon_{ik} \epsilon_{jl} + f_{abmn}' \bar{l}_{iaL}^C l_{jbL} \varphi_k^{(m)} \varphi_l^{(n)} \epsilon_{ij} \epsilon_{kl}, \tag{20}$$

where $\varphi^{(m)}$ are one or more scalar doublets. We expect f and f' to be roughly of order $1/M$; one-loop graphs would give values of order α^2/M.[13] The interaction (20) would produce a neutrino mass $m_\nu \simeq G_F^{-1} f$, or roughly 10^{-5} to 10^{-1} eV. This is well below any existing laboratory or cosmological limits, but there is no reason why this neutrino-mass matrix should be diagonal, and masses of this order might perhaps be observable in neutrino oscillation experiments.

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Note added.—After this paper was submitted for publication, I received a preprint from F. Wilczek and A. Zee [following Letter, Phys. Rev. Lett. 43, 1571 (1979)], which reaches similar conclusions about baryon-nonconserving processes.

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[5]H. Georgi, H. R. Quinn, and S. Weinberg, Phys. Rev. Lett. 33, 451 (1974). This paper showed that for a broad range of grand unified gauge models, the mass scale M is of order 10^{15} to 10^{16} GeV; the proton lifetime for typical M is very roughly of order 10^{32} yr; and $\sin^2\theta$ is close to 0.2. [This class of theories includes essentially all gauge models in which a simple grand gauge group is spontaneously broken in a single step at M to $SU(3)\otimes SU(2)\otimes U(1)$, and in which the fermions form generations of the same sort as for observed quarks and leptons.] These estimates have been improved by more detailed studies: A. Buras, J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B135, 66 (1978); D. Ross, Nucl. Phys. B140, 1 (1978); T. J. Goldman and D. A. Ross, Phys. Lett. 84B, 208 (1979); W. Marciano, Rockefeller University Report No. COO-2232B-173, 1979 (to be published); N. P. Chang, A. Das, and J. Perez-Mercader, to be published; C. Jarlskog and F. J. Yndurain, to be published; M. Machacek, Harvard University Report No. HUTP-79/A021, 1979 (to be published).

[6]This was not the case for the Pati-Salam model of Ref. 3, because SU(3) was assumed there to be spontaneously broken.

[7]Strictly speaking, this is correct if the couplings in the effective Lagrangian are defined at renormalization scales of order M. At ordinary energies E there are $\alpha \ln E/M$ renormalization effects (some calculated by Buras *et al.*, Ref. 5) but these corrections are at most of order unity, and do not affect our conclusions. Our approach is related to that of T. Appelquist and J. Carazzone, Phys. Rev. 11, 2856 (1975).

[8]Weinberg, Ref. 2, note (1). [The scalars X_S', X_S'' make no contribution to nucleon decay, and were previously omitted.]

[9]This conclusion was reached on essentially the same grounds by Machacek, Ref. 5.

[10]I understand that the general isospin properties of the effective interaction were worked out in a similar way in unpublished work by H. Georgi.

[11]Essentially the same relations have already been found by Machacek, Ref. 5. However, her derivation was in the context of specific models, and it was not clear which of these results would be more generally valid.

[12]General formulas for the possible interactions of X_S, X_V, and X_V' with quarks and leptons were given by Nanopoulos and Weinberg, Ref. 2.

[13]In the O(10) model, a term of form (20) is produced by a tree graph, with $f \approx G_F m_l^2/M$ [Georgi and Nanopoulos, Ref. 3]. Of course, f would vanish if $B-L$ were exactly conserved.