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IN UNIFIED MODELS OF QUARKS AND LEPTONS

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WHY IS B-L CONSERVED AND BARYON NUMBER NOT
IN UNIFIED MODELS OF QUARKS AND LEPTONS*

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ABSTRACT

Conservation of B-L and nonconservation of B are shown to follow simply from the weak isospin properties of quarks and leptons; namely that left-handed particles and right-handed antiparticles have weak isospin $1/2$, that all other fermions are singlets, and that particles with half-integral isospin can only be created or annihilated in pairs.

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Conservation of baryon number seems to be violated in any model which introduces bosons that transform a quark into a lepton or vice versa. Yet a proton can absorb a pion or a kaon and be transformed into a neutron or a hyperon without causing global non-conservation of electric charge or strangeness in strong interactions. Thus the mere existence of bosons which can change a fermion quantum number is not sufficient for violation of a conservation law. Thus there must be some additional reason why the new lepto-quark bosons introduced in unified models^{1,2} cannot carry baryon number to give a global conservation law in the same way that pions and kaons carry and conserve charge and strangeness.

The mysterious conservation of B-L in these models^{3,4} has been explained by a combination of SU(2) x U(1) selection rules, the classification of the known particles and the limitations of four point functions.^{5,6} We simplify this argument further and show that B-L conservation and B violation follow from the simple selection rule that the total number of particles with half-integral weak isospin can only change by an even number in a transition which conserves weak isospin. This selection rule can be written

$$\delta(N_{\frac{1}{2}} + \bar{N}_{\frac{1}{2}}) = 2n \quad (1a)$$

where $N_{\frac{1}{2}}$ and $\bar{N}_{\frac{1}{2}}$ are the total number of particles and of antiparticles respectively with isospin $\frac{1}{2}$. Since $2\bar{N}_{\frac{1}{2}}$ is manifestly an even integer, the selection rule (1a) is equi-

valent to

$$\delta(N_{\frac{1}{2}} - \bar{N}_{\frac{1}{2}}) = 2n . \quad (1b)$$

In the standard models for quarks and leptons, all left-handed particles and right-handed antiparticles have weak isospin $\frac{1}{2}$ and all right-handed particles and left-handed antiparticles have weak isospin zero. Thus the selection rule (1b) can be rewritten in terms of the numbers N_R , N_L , $\bar{N}_R$ and $\bar{N}_L$ of right-handed and left-handed particles and antiparticles. All quarks and leptons are assumed to have zero mass.

$$\delta(N_L - \bar{N}_R) = 2n . \quad (2)$$

If the only relevant particles are quarks with $B=1/3$, $L=0$ and leptons with $B=0$, $L=1$,

$$N_L - \bar{N}_R = (3B + L - H)/2 \quad (3)$$

where H is defined to be $+1$ for a right-handed particle and -1 for left-handed.

Substituting Eq. (3) into Eq. (2) gives

$$\delta(3B + L - H)/2 = 2n \quad (4a)$$

Since $2\delta B$ and $-\delta H$ are both even numbers, they can be subtracted from the selection rule (4a) to give

$$\delta(B - L - H) = 4n \quad (4b)$$

This selection rule can also be stated as the conservation of BL-parity⁶ defined by

$$\pi_{BL} = (-1)^{(B-L-H)/2} \quad (4c)$$

The selection rule (4) shows that B-L is conserved modulo 4 in all transitions where the helicity H does not change or changes by an even number. In four-point functions, where all the simple boson exchanges without derivative couplings have $\delta H = 0$ or 4, and where $\delta(B-L)$ cannot be as large as 4 because there are not enough external lines, B-L must be conserved.^{5,6} This derivation shows the result to be a simple consequence of the weak isospin classification of left-handed particles and right-handed antiparticles into doublets and everything else into singlets.

The "quasibaryon number" β can be defined as the combination of quantum numbers⁵

$$\beta = \frac{3(B-L) - H}{4} - Q + I_3 \quad (5)$$

where Q and I_3 are the electric charge and the third component of weak isospin.

It immediately follows that β is conserved in all processes which conserve Q , I_3 , H and B-L and in particular in all four point functions with no helicity change which conserve electric charge and weak isospin. However, β is seen to be exactly equal to the baryon number for all quark and lepton states⁵ except the right-handed up quark u_R and its conjugate left-handed $\bar{u}_L$. For any system of quarks and leptons

$$\beta = B - n(u_R) + n(\bar{u}_L)$$

where u denotes any quark with electric charge $+2/3$ and the result holds for any number of standard generations of quarks and leptons having massless left-handed neutrinos and no right-handed neutrinos.

For all processes where β is conserved, which includes all vector boson exchanges, B is conserved as long as $n(u_R) - n(\bar{u}_L)$ does not change. This includes the standard $SU(2) \times U(1)$ model of weak interactions where the u_R couples only to neutral currents which cannot change flavor. However, B must be violated by any gauge boson with a non-trivial coupling to u_R which changes it into something else which is not a u_R and with an additional coupling to any other particle. Four-point functions exist in which this boson is exchanged between a u_R and another object and the u_R is changed to something else and not restored at the other vertex. Then $n(u_R) - n(\bar{u}_L)$ changes and B must be violated if β is conserved.

Thus conservation of weak isospin is inconsistent with conservation of baryon number in processes mediated by a gauge boson which couples to the u_R quark in a non-trivial manner and allows a u_R quark to decay into something else. Baryon number, weak isospin and electric charge cannot all be conserved in any process having the form

$$u_R \rightarrow X + G \rightarrow X + Y + Z \quad (7)$$

where G is a gauge boson, and X , Y and Z can be any quark or

lepton state except a u_R . Any charge-conserving process which allows a u_R to decay into three fermions via an intermediate vector boson state must violate either weak isospin or baryon number.

The conservation of $B-L$ and nonconservation of B are seen to result from the weak isospin selection rule (1) and the standard weak isospin classification of quarks and leptons. These results hold in any model for four-point functions mediated by gauge bosons if weak isospin is conserved. For other n -point functions the more general selection rule (4b) holds in all transitions which conserve weak isospin. For example, the six-point function needed to change a neutron into an antineutron for neutron oscillations⁷ has $\delta(B-L) = 2$ and must have an odd number of helicity flips to conserve weak isospin. This transition is therefore forbidden if there are only vector boson exchanges which conserve H . In models with vector bosons and Higgs scalars, the six-point function describing $n \rightarrow \bar{n}$ must have an odd number of Higgs-fermion vertices; i.e. there must be at least one Higgs exchange between a fermion and a boson.

The results are easily generalized if new kinds of particles are introduced which have half-integral isospin. Eqs(2) and (3) can be extended to include these new particles to give new selection for processes in which these particles are created or absorbed but weak isospin is still conserved.

New bosons such as gauge vector or Higgs bosons can also be included by giving them the B , L and H quantum numbers defined by any fermion pair state to which they are coupled.

If B , L and H are not conserved, these quantum numbers may not be unique and can depend upon which fermion pair state is chosen. However, the value of π_{BL} and the selection rule (4) will be independent of the particular classification if Q and I_3 are conserved in all couplings of these bosons.

The selection rule (4b) will be violated if either the conservation of weak isospin or the conventional classification breaks down. This can occur, for example, if:

1. Dynamical mechanisms are introduced which violate weak isospin conservation. Mass terms which couple left and right-handed states are an example of such mechanisms. However, these must occur non-trivially within the n -point function, not only as corrections to give finite masses to external particles. Furthermore, the weak isospin breaking must give rise to transitions with $\delta I = 1/2$ in order to violate the selection rule (1) and its consequence (4b). Breaking described by integral δI does not affect these conclusions; e.g. giving unequal masses to the W and Z bosons.

2. New exotic external particles are introduced with the opposite correlation between helicity and weak isospin; e.g. a left-handed quark or lepton which is a weak isospin singlet. However, the above derivation breaks down only for transitions where such particles appear explicitly as external particles, not in loops which conserve weak isospin.

Although the quantum number H and the weak isospin are defined unambiguously only for zero mass fermions where helicity and chirality are equivalent, this restriction is irrelevant

in all the unified models under consideration,¹⁻⁴ where the quark and lepton masses are negligible on the scale of the grand unification mass. A physical process, such as proton decay or neutron-antineutron oscillations, is described by combining the B-violating n-point functions at the quark-lepton level with spectator quarks and possibly gluons to describe hadrons. However, all these processes of building hadrons out of quarks conserve B and L, and all the B and L violation occurs in an n-point function at the grand unification mass scale where the zero mass approximation is good. Thus even though weak isospin, H and the BL parity may not be defined for the hadron states, the selection rules for B and B-L conservation still apply.

As an example consider an initial nucleon state described by the MIT bag model. The nucleon at rest does not have a well defined weak isospin, H or π_{BL} . However, the bag model wave function is a state of three zero-mass quarks, which can be expanded in eigenfunctions of these quantum numbers, all with $B=1$ and $L=0$. The final state is obtained by looking at all possible transitions allowed by the particular weak decay model from all terms in this expansion. If these are all four-point functions which conserve weak isospin and conserve H because they are vector exchange, then they all conserve B-L. Thus all terms in the expansion of the final state have $B-L=1$ and the proton decay process conserves B-L.

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FOOTNOTES AND REFERENCES

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