[7] In a recent paper, J. C. Botke, D. J. Scalapino, and R. L. Sugar, to be published, a simple model is developed in which constant elastic and total cross sections arise naturally from multiperipheral-like intermediate states. The diffractive component does not have to be added on by hand.

[8] The arguments for various normalizations are discussed by W. R. Frazer *et al.*, University of California, Report No. 10P10-113 (to be published).

[9] G. Belletini, in *Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972*, edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973).

Is Baryon Number Conserved?

Jogesh C. Pati*
International Centre for Theoretical Physics, Trieste, Italy, and Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

and

Abdus Salam
International Centre for Theoretical Physics, Trieste, Italy, and Imperial College, London, England

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We suggest that baryon-number conservation may not be absolute and that an integrally charged quark may disintegrate into two leptons and an antilepton with a coupling strength $G_B m_p^2 \lesssim 10^{-9}$. On the other hand, if quarks are much heavier than low-lying hadrons, the decay of a three-quark system like the proton is highly forbidden (proton lifetime $\gtrsim 10^{28}$ y). Motivation for these ideas appears to arise within a unified theory of hadrons and leptons and their gauge interactions. We emphasize the consequences of such a possibility for real quark searches.

It is part of general belief in particle physics that conservation of baryon number is an absolute law of nature. Such a notion is but natural when one considers the extraordinary stability of the lightest known baryon, the proton, with a lifetime in excess of 10^{35} sec. In this note we wish to question whether this apparent proton stability truly reflects the conservation of baryon number to a similar degree.

Specifically, we have in mind the following possibility. Assume that the proton is made up in some sense of three quarks, each quark (q) carrying baryon number $B=1$ and an integral electric charge. Assume that quarks and diquarks (if the latter exist) are heavier than the low-lying hadrons. Assume further that a quark can decay into two of the known leptons ($l=\nu_e, e^-, \nu_\mu, \mu^-$) and an antilepton, the decay being described by an effective Lagrangian

$$\mathcal{L}_{\mathrm{eff}}=(G_B/\sqrt{2})(\bar{q}l)(\bar{l}l)+\mathrm{H.c.} \tag{1}$$

This decay violates conservation of baryon and lepton (L) numbers, but conserves fermion number F where $F=B+L$.

Our point is this: If states with quark and diquark quantum numbers are heavier than the low-lying hadrons, a proton ($B=3$, $F=3$) can have a real decay only to three leptons plus mesons, or four leptons plus an antilepton, etc. Since this involves a violation of baryon number by three units, the lowest-order amplitude in G_B in which a proton can decay[1] is therefore G_B^3. Assume that $G_B m_p^2 \lesssim 10^{-9}$. (We give later our theoretical reasons for G_B being less than the decay constant for $|\Delta S| \neq 0$ neutral semileptonic transitions, which is of order $G_F\alpha^2$ empirically.) We then find that the decay $q \rightarrow l+l+\bar{l}$ may be associated with a lifetime as short as 10^{-10} sec, say (depending on quark mass), whereas the proton's lifetime could still be far in excess of 10^{35} sec because of the high degree of forbiddenness of its decay. Such a model would therefore show that (i) quarks (if they exist) may exhibit unexpected decay properties involving violation of baryon number as well as lepton number without conflicting with the observed degree of stability of the proton, and (ii) there is the possibility that there is no stable quark, contrary to present belief. This may be one reason why conventional searches for quarks have been unsuccessful (especially if $\tau_q \lesssim 10^{-10}$ sec). (Note that if quarks were fractionally charged, electric-charge conservation would imply that a stable quark must exist unless there were lighter fractionally charged leptons[2] into which the quarks could decay.)

Before giving the motivation which led us to consider an effective interaction of the type (1) —*and we stress that the general considerations above hold irrespective of any specific model* —we give some order-of-magnitude estimates for typical quark and proton decay widths (see Table I). The quark decay width follows directly from Eq. (1):

$$\Gamma(q\rightarrow l+l+\bar{l})=G_B{}^2 m_q{}^5/24(2\pi)^3 = \lambda^2(3\times10^7\ \mathrm{sec}^{-1})\left(\frac{m_q}{10\ \mathrm{GeV}}\right)^5, \tag{2}$$

where we have put $G_B=\lambda G_F\alpha^2$ (we estimate $\lambda\lesssim1$; see below). Two typical proton decay amplitudes (M) and corresponding rates ($\Gamma=|M|^2\rho$, where ρ is the phase-space factor) are listed in Table I. The quantities m_q and m_p are quark[3] and proton masses; A_4 and A_5 are numerical factors arising out of four- and five-particle phase-space integrations, which depend somewhat on precise matrix elements [usually they are $\gg1$; for example $A_3=12$, see Eq. (2)]; Λ is a cutoff, which may be of the order of a few GeV (as in the K_L-K_S mass-difference calculation). Using Table I, we obtain for a typical proton decay[4]

$$\Gamma(p\rightarrow3l+\pi)=2\times10^{-39}\lambda^6/A_4\ \mathrm{sec}^{-1} \tag{3}$$

for $m_q=10$ GeV and $\Lambda=2m_p$. Thus for $\lambda\lesssim1$, $\Gamma_p\lesssim2\times10^{-39}\ \mathrm{sec}^{-1}$. Although one may not take the precise estimates given above too seriously, the main point we wish to emphasize is that the high degree of forbiddenness of the proton decay relative to the quark decay appears to be sufficient to lay open the possibility that the proton may be comfortably stable ($\tau_p>10^{28}$ yr) and yet the quarks decaying into leptons sufficiently short lived.

Since $G_B m_p{}^2\approx10^{-9}$ implies a characteristic energy (or intermediate meson mass) of the order of 3×10^4 GeV, one may expect that at (cosmic-ray) energies of this order, reaction rates for the processes $e+p$ or $p+p\rightarrow$ leptons + antileptons, etc., would attain unitarity limit and effectively become strong. Thus a study of multilepton-induced showers at high cosmic-ray energies may be one way of testing the ideas presented above. A clearer test could hopefully be provided by extending the search for real integrally charged quarks at the CERN intersecting storage rings and the National Accelerator Laboratory to detect possible disintegration of quarks into *energetic* leptons ($q\rightarrow l+l+\bar{l}$, $q\rightarrow l+\pi$, $q\rightarrow l+\gamma$, ..., etc.). One should allow for $\tau_q\gtrsim10^{-10}$ sec on the one hand and perhaps[5] as short as 10^{-12} to 10^{-13} sec on the other.

Our basic motivation for B nonconservation comes from a recent attempt[1,6] at a gauge theory of strong, weak, and electromagnetic interactions. To construct a unified, anomaly-free, renormalizable gauge model we suggested that a system of twelve integrally charged quarks (nine of Han-Nambu variety, and three charmed quarks) plus the four known leptons ($\nu_e, e^-, \mu^-, \nu_\mu$) be combined in a ($\underline{4}$, $\underline{4}$*) representation F of an $\mathrm{SU}(4)_{L+R}{}'\otimes\mathrm{SU}(4)_{L+R}{}''$ group structure,

$$\boldsymbol{F}=\begin{pmatrix} \mathcal{P}_a{}^0 & \mathcal{P}_b{}^+ & \mathcal{P}_c{}^+ & \nu_e \\ \mathfrak{N}_a{}^- & \mathfrak{N}_b{}^0 & \mathfrak{N}_c{}^0 & e^- \\ \Lambda_a{}^- & \Lambda_b{}^0 & \Lambda_c{}^0 & \mu^- \\ \chi_a{}^0 & \chi_b{}^+ & \chi_c{}^+ & \nu_\mu \end{pmatrix}. \tag{4}$$

The strong interactions were introduced by gauging an $\mathrm{SU}(3)_{L+R}{}''$ subgroup of $\mathrm{SU}(4)_{L+R}{}''$, the conventional weak interactions by gauging an $[\mathrm{SU}_L(2)']$ subgroup of $\mathrm{SU}(4)_L{}'$, while the electromagnetic gauges spanned over generators of *both* SU(4)′ and SU(4)″, i.e.,

$$Q=(I_3{}'+\tfrac{1}{2}Y'-\tfrac{2}{3}C')_{L+R} +(I_3{}''+\tfrac{1}{2}Y''-\tfrac{2}{3}C'')_{L+R}. \tag{5}$$

TABLE I. Estimates of typical proton decay modes. We have not exhibited factors of $(2\pi)^{-n}$ ($n>0$) in the matrix element M, which usually arise from virtual loops. These suppress proton decay rate still further.

Decay	M	ρ	Γ
$p\rightarrow l+l+l+\pi$	$\left(\frac{G_B}{\sqrt{2}}\right)^3\left(\frac{\Lambda}{m_q}\right)^3\Lambda^3$	$\frac{M_p{}^7}{A_4(2\pi)^5}$	$m_p\left(\frac{G_B m_p{}^2}{\sqrt{2}}\right)^6\left(\frac{\Lambda}{m_q}\right)^6\left(\frac{\Lambda}{m_p}\right)^6\frac{1}{A_4(2\pi)^5}$
$p\rightarrow l+l+l+l+\bar{l}$	$\left(\frac{G_B}{\sqrt{2}}\right)^3\left(\frac{\Lambda}{m_q}\right)^3\Lambda$	$\frac{M_p{}^{11}}{A_5(2\pi)^7}$	$m_p\left(\frac{G_B m_p{}^2}{\sqrt{2}}\right)^6\left(\frac{\Lambda}{m_q}\right)^6\left(\frac{\Lambda}{m_p}\right)\frac{1}{A_5(2\pi)^7}$

The theory at this stage had no exotic consequences except for the unusual unification of hadronic matter ($B=1$, $L=0$) with leptonic matter ($B=0$, $L=1$) within the *same* multiplet of a common symmetry structure $SU(4)'\otimes SU(4)''$.

But in order that such a unification be dynamically compelling, one must gauge sufficient degrees of freedom (consistent with established[7] selection rules) to ensure transformability of leptons into baryons. This still does not imply nonconservation of baryon-lepton numbers because appropriate gauge bosons could carry these numbers. What we want to show is that if in addition to the subgroups mentioned above we had also gauged the remaining degrees of freedom of $SU(4)'$ and $SU(4)''$, or even a non-Abelian subset (stated below) such that the electric current is expressed as a sum of *non-Abelian* currents from both groups $SU(4)'$ and $SU(4)''$, the requirement of electric-charge conservation—expressed in terms of masslessness of the photon—together with the twin requirements of renormalizability and appropriate[8] massiveness of all other gauge bosons, necessarily appears to lead to lepton-baryon-number nonconservation.

To demonstrate this, consider the local gauge structure[9,10] $SU(4)_L'\otimes SU(4)_R'\otimes SU(4)_{L+R}''$ {although the essential ingredients of the argument become manifest already at the stage of the smaller gauge symmetry $[SU(2)_L']\otimes[SU(2)_R']\otimes SU(4)_{L+R}''$, preferable for reasons connected with anomalies}. Let $W_{ij}^{L,R}$ and V_{ij} ($i,j=1,2,3,4$) represent the fifteen-plet of gauge mesons associated with the groups $SU(4)_{L,R}'$ and $SU(4)_{L+R}''$ with $J_{ij}'^{L,R}$ and J_{ij}'' denoting the associated currents. Note that the quantum numbers B, L associated with these currents are as follows:

$$J_{ij}'^{L,R}\ (\text{all } i \text{ and } j),\quad B=L=0;$$

$$J_{ij}''\ (i,j=1,2,3;\ i=j=4),\quad B=L=0;$$

$$J_{ij}''\ (i=1,2,3;\ j=4),\quad B=1,\ L=-1;$$

$$J_{ij}''\ (i=4;\ j=1,2,3),\quad B=-1,\ L=+1;$$

the last two groups being exotic. The point to be emphasized is that unless the theory forces a mixing of the nonexotic currents ($B=L=0$) with the exotic ones (with $B\neq 0$, $L\neq 0$), the mere existence of such currents and the corresponding gauge mesons would not violate B-L conservation. Such a mixing, however, appears necessary if one attempts to give masses to all gauge mesons (with the sole exception of the photon) through a Higgs-Kibble mechanism. This is because with the electric charge expressed as a sum of non-Abelian generators [as given by Eq. (5)], appropriate massiveness of all gauge bosons other than the photon can be secured only[11] by postulating, among other representations, the existence of a mixed representation of Higgs-Kibble σ particles—typically a $(\underline{1}, \underline{4}, \underline{4}^*)$ representation of $SU(4)_L'\otimes SU(4)_R'\otimes SU(4)_{L+R}''$—with expectation values in the sequence indicated:

$$\langle\sigma\rangle_{ij}=\alpha_i\delta_{ij}\quad (i,j=1,2,3,4). \tag{6}$$

Quite clearly, the gauge term in the Lagrangian $|g_RW^R\langle\sigma\rangle+f\langle\sigma\rangle V|^2$ [where g_R and f are the coupling constants associated with weak $SU(4)_R'$ and strong $SU(4)_{L+R}'$ gauge groups, respectively] induces not only the appropriate mixing of neutral V's and the W's which go to make up the photon but also a mixing of the exotic V's with W^R's, coupled to $B=0=L$ currents. It is this mixing which is responsible for B-L nonconservation.

A typical term in the effective current-current Lagrangian induced by the above mixing is of the form

$$\mathcal{L}_B=G_B(\overline{\mathcal{P}}_a{}^0\nu_e+\overline{\mathcal{N}}_a{}^-e^-+\overline{\lambda}_a{}^-\mu^-+\overline{\chi}{}^0\nu_\mu)\times(C^0+\overline{\nu}_\mu\nu_e)_R+\text{H.c.}, \tag{7}$$

where $C^0=(\overline{\mathcal{P}}_a{}^0\chi_a{}^0+\overline{\mathcal{P}}_b\chi_b{}^++\overline{\mathcal{P}}_c\chi_c{}^+)_R$ is the charm current and $\mathcal{L}_B$ is part of the structure

$$\alpha_1\alpha_4J_{14}''J_{41}'^R+\alpha_2\alpha_4J_{24}''J_{42}'^R+\alpha_3\alpha_4J_{34}''J_{43}'^R+\text{H.c.} \tag{8}$$

To obtain an estimate of G_B, first note that exchanges of the exotic V mesons [as well as exchanges of $W_{3i}{}^R$ ($i=1,2$)] induce neutral semileptonic $|\Delta S|\neq 0$ transitions with effective strength $\simeq f^2/m_x{}^2$, where m_x is an exotic meson mass. In order that this be consistent with observed limits, $f^2/m_x{}^2$ must be $\lesssim G_F\alpha^2$. Thus[12] $m_x\gtrsim f(3\times 10^4$ GeV). Since $G_B=\kappa(f^2/m_x{}^2)$, where κ is a mixing parameter (whose detailed value depends on the mass matrix), we infer that empirically $G_B\leqslant G_F\alpha^2$.

It is amusing to note that, depending on the details of the model chosen for the Higgs-Kibble scalars (and whether μ^- or e^- is the "strange" lepton), one will encounter varying selection rules for quark and proton decays. The precise structure of the B-L-nonconserving interaction obtained above leads to quark decays of the following variety:

(A) $(\mathcal{P}_a{}^0, \mathcal{N}_a{}^-, \lambda_a{}^-) \to (\nu_e, e^-, \mu^-) + (\nu_\mu + \bar{\nu}_e)$.
(B) $(\mathcal{P}_b{}^+, \mathcal{N}_b{}^0, \lambda_b{}^0) \to (\nu_e, e^-, \mu^-) + (\nu_\mu + e^+)$.
(C) $(\mathcal{P}_c{}^+, \mathcal{N}_c{}^0, \lambda_c{}^0) \to (\nu_e, e^-, \mu^-) + (\nu_\mu + \mu^+)$.

These would lead to a proton's decay to seven or nine leptons (including antileptons), but not to $3l+\pi$ or $4l+\bar{l}$. One may note that within the smaller gauge structure $\{[\mathrm{SU}(2)_L{}'] \otimes [\mathrm{SU}(2)_R{}'] \otimes \mathrm{SU}(4)_{L+R}{}''\}$, B-L nonconservation proceeds only through the term $J_{34}{}''(J_{43}{}'^R + J_{12}{}'^R)$. This will allow decays of the type (C), but not of (A) and (B). In this case, since the proton is made up of (a, b, c) quarks, one can show that its decay is further suppressed[13] at least by additional factors of α.

Since the characteristic energies ($\approx 10^4$–10^5 GeV) discussed above (which, we stress, represent a *new scale* in particle physics) are not the energies encountered in normal star interiors, one does not expect significant astrophysical implications of B-L nonconservation except in the early stages of the universe (when baryons may have been produced from energetic lepton-lepton collisions or vice versa) and possibly in blackholes and quasars.

To conclude, while arguments based on a particular set of theoretical ideas are never compelling, the general considerations on forbiddenness of proton decay in a heavy quark model remain and need experimental verification. If the gauge ideas are correct, we find it amusing that the only known massless gauge particle is the photon. Could it be that the electric charge is the only non-Abelian[14] conserved charge in nature?

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[1] This remark orginates from Appendix A of J. C. Pati and A. Salam, Phys. Rev. D 8, 1240 (1973). The motivation for baryon-lepton–number nonconservation in the present paper is very different from that presented in this Appendix.

[2] A. Salam and J. C. Pati, Phys. Lett. 43B, 311 (1973).

[3] The characteristic appearance of $(G_B/m_q)^3$ in the proton-decay matrix elements is due to the fact that the unitarity sum for ImM necessarily contains a product of the three physical-quark–decay matrix elements and hence the real part is proportional to $\sum_E G_B{}^3(m_q - E)^{-3}$.

[4] Note that of the value given in Eq. (3), 6×10^{-35} sec^{-1} comes from a characteristic three-body decay width alone (if such a decay were allowed) i.e., $\Gamma(p \to 3l) = (96\pi^3)^{-1}(2^{-3/2}G_B{}^3 m_p{}^6)^2 m_p$, with $G_B m_p{}^2 = G_F \alpha^2$.

[5] Because of the uncertainty in the estimate of the proton-decay matrix element, it is possible that the quark lifetime could even be of order 10^{-12} to 10^{-13} sec without conflicting with the proton lifetime, especially if additional selection rules are involved in proton decay (see also remarks below).

[6] C. Itoh, T. Miamikawa, K. Miura, and T. Watanabe, "Unified Gauge Theory of Weak Electromagnetic and Strong Interactions" (to be published). This model is similar to that of Ref. 1, except that quarks are fractionally charged while leptons are integrally charged and the gauge bosons are massless. There would be no possibility of quarks decaying into leptons in this scheme.

[7] The whole purpose of the introductory section was to question whether baryon conservation is indeed all that well established.

[8] Consistent with approximate global SU(3)'' symmetry and effectively weak lepton interactions [so that $\alpha_1 \simeq \alpha_2 \simeq \alpha_3 \neq 0$ and $\alpha_4 \neq 0$ and large in Eq. (6)].

[9] The desirability of gauging an extended group structure was suggested in Ref. 1. The bigger group structure $\mathrm{SU}(4)_L{}' \otimes \mathrm{SU}(4)_R{}' \otimes \mathrm{SU}(4)_{L+R}{}''$ leads to anomalies. On the other hand a simple and elegant scheme is obtained within the smaller gauge symmetry $\mathrm{SU}(2)_L{}' \otimes \mathrm{SU}(2)_R{}' \otimes \mathrm{SU}(4)_{L+R}{}''$, which we consider in some detail in a forthcoming note.

[10] D. Ross, to be published, has independently considered the consequences of gauging $\mathrm{SU}(4)' \times \mathrm{SU}(4)''$ within the unified model of Ref. 1. His work confirms the conclusion regarding B-L nonconservation in such a scheme.

[11] The necessity for such a representation involves a longer discussion and will be given elsewhere.

[12] It is well known that suppression due to large masses is not retained in general by loop diagrams (see for example, S. Weinberg, Phys. Rev., to be published. Preliminary studies reveal that in the model presented here B and L nonconservations are suppressed by heavy masses even in loop diagrams. This is to be considered in detail elsewhere.

[13] It is even possible that the proton could be made absolutely stable in this model, provided there exists an additional particle (meson) in the theory, which is also absolutely stable and heavier than the proton (see Appendix A of Ref. 1 for details of this mechanism).

[14] There is, of course, still the possibility of gauging the U(1) Abelian generator, corresponding to fermion-number conservation in the theory.