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IS BARYON NUMBER CONSERVED? *

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ABSTRACT

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 $G_B\, m_p^2 \lesssim 10^{-9}$. If quarks are much heavier than low-lying hadrons, the decay of a three-quark system like the proton, on the other hand, is highly forbidden (proton lifetime $\gtrsim 10^{28}$ years). A possible motivation for these ideas appears to arise within a unified gauge theory of fundamental interactions, which places upper limits on G_B through its relation with the effective constant characteristic of $|\Delta S| \neq 0$ neutral semileptonic transitions (i.e. empirically $G_B \lesssim G_F\, \alpha^2$). It is suggested that quark disintegration into leptons may be searched for through lepton-induced extensive cosmic-ray showers.

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1. 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 lifetime in excess of 10^{35} seconds. 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 ($\ell = \nu_e , e^- , \nu_\mu , \mu^-$) and an antilepton, the decay being described by an effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \frac{G_B}{\sqrt{2}} (\bar{q}\ell) (\bar{\ell}\ell) + \text{h.c.} \qquad (1)$$

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

Our point is this: if the quark and the diquark are heavier than the proton, the lowest-order amplitude in G_B in which a proton ($B = 3$, $F = 3$) can decay into three leptons and mesons, or four leptons and an antilepton, etc. is $^{1)}$ G_B^3 . Assume that $G_B m_p^2$ is of the order of or less than 10^{-9} ; (later in Sec.4 we give our theoretical reasons for G_B being less than the decay constant characteristic of $|\Delta S| \neq 0$ neutral semi-leptonic transitions (like $K_L \to \mu^+ + \mu^-$) and which equals $G_F \alpha^2$ empirically). We then find that the decay $q \to \ell+\ell+\bar{\ell}$ may be associated with a lifetime as short as a microsecond (depending on quark mass), whereas the proton's lifetime could be far in excess of 10^{35} secs, on account 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. (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 of which the presently known leptons are composite 2).)

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).

Write $\Gamma = |M|^2 \rho$ where M is the matrix element and ρ is the phase-space factor. In Table I m_q and m_p are quark and proton masses; A_4, A_5, A_7 are factors (usually > 1) which depend on precise matrix element and phase-space integrations, and Λ is a cut-off, which may be of the order of a few BeV. 3)

Assuming that $G_B \leq G_F \alpha^2$, we obtain for quark decay

$$\Gamma_q = \lambda^2 \times 10^8 \ \mathrm{sec}^{-1} \times \begin{pmatrix} 1 \\ 80 \end{pmatrix} \begin{array}{l} m_q = 10 \ \mathrm{BeV} \\ m_q = 30 \ \mathrm{BeV} \end{array}$$

and for a typical proton decay (see Table I)

$$\Gamma_{p \to 3\ell+\pi} = \frac{\lambda^6}{A_4} \times 10^{-40} \ \mathrm{sec}^{-1}$$

for $m_q = 10$ BeV and $\Lambda \approx 2m_p$, where $\lambda = G_B/(G_F \alpha^2)$. The important point to note is that, of this value, 10^{-35} sec^{-1} comes from a characteristic factor for three-body decay width alone, i.e. $\Gamma_p(p \to 3\ell) \approx (96\pi^3)^{-1} m_p [2^{-1/2} G_F^3 m_p^6 \alpha^6]^2$. Even if $\lambda \approx 1$ (and in Sec.4 we estimate that $\lambda \lesssim 1$) we find $\Gamma_p \lesssim 10^{-40}$ sec^{-1}. Clearly the proton is comfortably stable and the quark sufficiently short-lived. Since $G_B m_p^2 \approx 10^{-9}$ implies a characteristic mass of the order of 3×10^4 BeV , one may expect that at (cosmic-ray) energies of this order, reaction rates for the processes $e + p$ or $p + p \to$ leptons + antileptons, etc., would attain unitarity limit and effectively become strong. Thus a study of multi-lepton-induced showers at high cosmic-ray energies may provide tests of the ideas presented above. In particular, it would be interesting to search for possible disintegration of integrally-charged quarks into leptons.

2. Our basic motivation for B violation comes from a recent attempt 1),4) 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 (ν_e , e^- , μ^-, ν_μ) be combined in a $(4,\bar{4})$ representation F of an $SU(4)'_{L+R} \times SU(4)''_{L+R}$ group structure

$$F = \begin{pmatrix} p_a^0 & p_b^+ & p_c^+ & \nu_e \\ n_a^- & n_b^0 & n_c^0 & e^- \\ \Lambda_a^- & \Lambda_b^0 & \Lambda_c^0 & \mu^- \\ \chi_a^0 & \chi_b^+ & \chi_c^+ & \nu_\mu \end{pmatrix} .$$

The strong interactions were introduced by gauging $SU(3)''_{L+R}$ subgroup of $SU(4)''_{L+R}$; the conventional weak interactions by gauging the $[SU_L(2)']$ subgroup of $SU(4)'_L$, while the electromagnetic gauges spanned over generators of <u>both</u> SU(4)' and SU(4)" , i.e.

$$Q = \left[I_3' + \frac{Y'}{2} - \frac{2}{3} C'\right]_{L+R} + \left[I_3'' + \frac{Y''}{2} - \frac{2}{3} C''\right]_{L+R} .$$

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 $SU(4)' \times SU(4)''$. We argued that this unification was really no more unconventional than the usual combining of charged and neutral particles (μ^- and ν_μ, for example) within the same symmetry structure ($U(1) \times SU(2)$ in this case) and the subsequent gauge unification of forces (electromagnetic and weak) with effective couplings as different as $1 : 10^{-3}$.

But in order that such a unification be dynamically compelling, one must gauge sufficient degrees of freedom (consistent with established 5) selection rules to ensure transformability of leptons into baryons. This still does not imply violation 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 massiveness of all other gauge bosons) necessarily appears to lead to lepton-baryon number violation. The argument is the following. If for a non-abelian group structure masslessness of gauge particles is related in a one-one fashion with conserved currents, then all currents except the electromagnetic must be (spontaneously) violated, including C'' which in this model represents lepton number ($L=C'' + \frac{F}{4}$).

3. To make the idea more plausible consider the local gauge structure 6),7) $SU(4)'_L \times SU(4)'_R \times SU(4)''_{L+R}$ (although the essential ingredients of the argument become manifest already at the stage of the smaller gauge symmetry $[SU(2)'_L] \times [SU(2)'_R] \times SU(4)''_{L+R}$, which may be preferable for reasons connected with anomalies). Let $W^{L,R}_{ij}$ and V_{ij} ($i,j = 1,2,3,4$) represent the 15-plet of gauge mesons associated with the groups $SU(4)'_{L,R}$ and $SU(4)''_{L+R}$ with $J'^{L,R}_{ij}$ and J''_{ij} denoting the associated currents. Note that the quantum numbers B and L associated with these currents are as follows:

$J'^{L,R}_{ij}$ (all i and j): $B = L = 0$

J''_{ij} (i,j = 1,2,3 and i = j = 4) ; $B = L = 0$.

J''_{ij} (i = 1,2,3 ; j = 4) $B = 1$, $L = -1$

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

$\left.\begin{array}{l} B = 1 , L = -1 \\ B = -1, L = +1 \end{array}\right\}$ "exotic" .

The point to be emphasised is that unless the theory forces a mixing of the non-exotic 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 baryon-lepton 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.

The detailed arguments will be elaborated elsewhere.6) Its barest bones are the following. The photon current, in the notation used above, is a mixture of $(J'_{11} + J'_{44}) + (J''_{11} + J''_{44})$. In Higgs-Kibble theory, a mixing of primed and double-primed generators together with massiveness of all gauge bosons other than the photon, can be secured only 8) by postulating the existence of a mixed spin-zero representation of Higgs-Kibble σ particles - typically a $(1,4,\bar{4})$ representation of $SU(4)'_L \times SU_R(4)' \times SU(4)''_{L+R}$ - with expectation values in the sequence indicated:

$$\langle\sigma\rangle = \begin{pmatrix} \alpha & & & 0 \\ & \beta & & \\ & & \gamma & \\ 0 & & & \delta \end{pmatrix} . \tag{2}$$

Quite clearly the gauge term in the Lagrangian $|g_R W \langle\sigma\rangle + f \langle\sigma\rangle V|^2$ (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 baryon-lepton violation.

4. A typical term involving baryon-lepton number violation, induced by the above mixing is of the form

$$\mathcal{L}_B = G_B \left(\bar{p}_a^0 \nu_e + \bar{n}_a^- e^- + \bar{\lambda}_a^- \mu^- + \bar{\chi}^0 \nu_\mu\right) (C^0 + \bar{\nu}_\mu \nu_e)_R + \text{H.C.}$$

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

$$(\alpha^2 + \delta^2) J''_{14} J'^R_{41} + (\beta^2 + \delta^2) J''_{24} J'^R_{42} + (\gamma^2 + \delta^2) J''_{34} J'^R_{43} .$$

To obtain an estimate of G_B, first note that exchanges of the exotic V mesons (as well as exchanges of W^R_{3i} (i = 1,2)) induce neutral semileptonic $|\Delta S| \neq 0$ transitions with effective strength $\propto f^2/m_x^2$ 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 [9)] $m_x \gtrsim f(3 \times 10^4 \text{ BeV})$. 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 $G_B \leq G_F \alpha^2$.

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 baryon-lepton number violating interaction obtained above leads to quark decays of the following variety:

$$(p_a^0 , n_a^- , \lambda_a^-) \to (\nu_e , e^- , \mu^-) + (\nu_\mu + \bar{\nu}_e) \qquad \text{(A)}$$

$$(p_b^+ , n_b^0 , \lambda_b^0) \to (\nu_e , e^- , \mu^-) + (\nu_\mu + e^+) \qquad \text{(B)}$$

$$(p_c^+ , n_c^0 , \lambda_c^0) \to (\nu_e , e^- , \mu^-) + (\nu_\mu + \mu^+) . \qquad \text{(C)}$$

These would lead to proton's decay to 7 or 9 leptons or 3 (or 5) leptons plus charmed mesons like C^0. One may note that within the smaller gauge structure $[(SU(2)'_L) \times (SU(2)'_R) \times SU(4)''_{L+R}]$, baryon-lepton number violation proceeds only through the term $J''_{34}\, J'^{R}_{43}$. 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 (10) by additional factors of G_F.

5. Since the age of the Universe (10^{10} years) is smaller than τ_p and since the characteristic energies ($\approx 10^4$–10^5 BeV) discussed in Sec.1 (which we stress, represent a new scale in particle physics) are not the energies encountered in normal star interiors, one does not expect startling astrophysical implications of baryon-lepton violation except at the early stages of the Universe, when baryons may have been produced from energetic lepton-lepton collisions or vice versa.

To conclude, while arguments based on a particular set of theoretical ideas are never compelling, the general considerations of Sec.1 on forbiddnesses 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 11) conserved charge in nature?

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REFERENCES AND FOOTNOTES

1) This remark orginates from Appx. A of an earlier paper, J.C. Pati and Abdus Salam, Phys. Rev. D (15 August 1973, to be published). The motivation for baryon-lepton violation in the present paper is, however, different from that presented in this Appendix.

2) Abdus Salam and J.C. Pati, Phys. Letters. 43B, 311(1973).
Fractionally charged leptons of which the known leptons may be composite were introduced in this note. One could conceive of a new model based entirely on fractionally charged quarks and similarly charged leptons.

3) The characteristic appearance of $(G_B/m_q)^3$ in the proton decay matrix elements is a reflection of the fact that all three quarks in the proton must decay virtually or otherwise. The unitarity sum for Im M will therefore necessarily contain 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) C. Itoh, T. Miamikawa, K. Miura and T. Watanabe, "Unified gauge theory of weak electromagnetic and strong interactions", preprint 1973. This model is similar to that of Ref.1, except that quarks are fractionally charged while leptons are integrally charged. There would be no possibility of quarks decaying into leptons in this scheme.

5) The whole purpose of Sec.1 was to question whether baryon conservation is indeed all that well established.

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

7) D. Ross, Imperial College, London, ICTP, July 1973, has independently considered the consequences of gauging $SU(4)' \times SU(4)''$ within the unified model of Ref.1. His work confirms the conclusion regarding baryon-lepton number violation in such a scheme.

8) The necessity for such a representation involves a longer discussion and will be given in Ref.6. As far as we have been able to examine, by considering various representations, our conclusions about violations generally hold. One must, however, realize that arguments of Sec.3, like all arguments in Higgs-Kibble theory, are representation dependent. It is therefore desirable that the general group-theoretic argument along the lines presented at the end of Sec.2 be sharpened.

9) We are aware of the type of difficulty pointed out by S. Weinberg (MIT preprint, No. 343, 1973) in respect of radiative corrections giving large finite effects in spite of large masses of the gauge particles. This subtle point is being investigated.

10) 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 Appx.A of Ref.1 for details of this mechanism).

11) There is, of course, the possibility of gauging the U(1)-abelian generator, corresponding to fermion number in the theory. The associated gauge meson may be massive with no serious restriction on its coupling constant. On the other hand, if it is massless, its effective coupling constant must be less than $10^{-8}\ G_N\ m_e^2$ ($G_N\ m_e^2 \approx 10^{-44}$ is the Newtonian constant) in accordance with the well-known arguments of Lee and Yang (Phys. Rev. 98, 1501 (1955)).

TABLE I [†]

Decay	M	ρ	Γ
$q \rightarrow \ell+\ell+\bar{\ell}$	$\frac{G_B}{\sqrt{2}}$	$\frac{M_q^5}{12(2\pi)^3}$	$m_q \left(\frac{G_B\, m_p^2}{\sqrt{2}}\right)^2 \cdot \left(\frac{m_q}{m_p}\right)^4 \frac{1}{12(2\pi)^3}$
$p \rightarrow \ell+\ell+\ell+\pi$	$\left(\frac{G_B}{\sqrt{2}}\right)^3 \left(\frac{\Lambda}{m_q}\right)^3 \quad \Lambda^3$	$\frac{M_p^7}{A_4(2\pi)^5}$	$m_p \left(\frac{G_B\, m_p^2}{\sqrt{2}}\right)^6 \left(\frac{\Lambda}{m_q}\right)^6 \left(\frac{\Lambda}{m_p}\right)^6 \frac{1}{A_4(2\pi)^5}$
$p \rightarrow \ell+\ell+\ell+\ell+\ell+\bar{\ell}$	$\left(\frac{G_B}{\sqrt{2}}\right)^3 \left(\frac{\Lambda}{m_q}\right)^3 \quad \Lambda$	$\frac{M_p^{11}}{A_5(2\pi)^7}$	$m_p \left(\frac{G_B\, m_p^2}{\sqrt{2}}\right)^6 \left(\frac{\Lambda}{m_q}\right)^6 \left(\frac{\Lambda}{m_p}\right) \frac{1}{A_5(2\pi)^7}$
$p \rightarrow \ell+\ell+\ell+\ell+\ell+\ell+\bar{\ell}+\bar{\ell}$	$\left(\frac{G_B}{\sqrt{2}}\right)^3 \left(\frac{\Lambda}{m_q}\right)^3 \quad \frac{1}{\Lambda^2}$	$\frac{M_p^{17}}{A_7(2\pi)^{11}}$	$m_p \left(\frac{G_B\, m_p^2}{\sqrt{2}}\right)^6 \left(\frac{\Lambda}{m_q}\right)^6 \cdot \left(\frac{m_p}{\Lambda}\right)^4 \frac{1}{A_7(2\pi)^{11}}$

[†] 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.