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SPONTANEOUS BREAKING OF GLOBAL BARYON NUMBER SYMMETRY

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A B S T R A C T

We study the possibility that the $U(1)_B$ global symmetry associated with baryon number is spontaneously broken. We present realistic examples implemented in the context of a suitably extended standard $SU(2)_L \times U(1) \times SU(3)_C$ model and of a composite model of quarks and leptons. The global $U(1)_B$ symmetry in both cases is spontaneously broken at a relatively low mass scale without any conflict with observations. The dominant baryon number non-conserving process in these models obeys the $\Delta B = 2$ selection rule.

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1. There was a common belief among particle physicists that exact global symmetries of nature could not be spontaneously broken by the vacuum, since that would lead to massless particles implying the existence of long range forces. This myth has been challenged in a recent paper¹⁾. It has been shown¹⁾ in the context of realistic gauge models of electroweak interactions that global lepton number symmetry can be spontaneously broken without any conflict with observations. The associated Goldstone boson - the Majoron - has only a γ_5 coupling to ordinary matter with a strength $\sim G_F(m_e^3/M_L)$ (where M_L is the scale of lepton number breaking), which is much below the existing limits on such couplings for $M_L \gtrsim 1$ TeV. This idea has subsequently been extended to an alternative model²⁾ with low mass lepton number breaking³⁾ with $(M_L/M_W) \lesssim 10^{-6}$.

The immediate question that comes to mind is: are there other global symmetries, which could be broken in this way^{*)}? It is the purpose of this paper to discuss examples of realistic models where the global symmetry associated with baryon number, $U(1)_B$, can be broken without any conflict with existing data if the breaking scale M_B is appropriately chosen. Even without committing ourselves to any of the specific models presented, we believe it is an interesting result that M_B need not be superheavy (i.e., $\sim 10^{15}$ GeV) but can be as low as $1 \div 10$ TeV. The characteristic B violating process in these models is neutron-antineutron oscillation. We discuss three examples: (i) an $SU(2)_L \times U(1) \times SU(3)_C$ gauge model, where $M_B \gtrsim 10^4$ GeV; (ii) a model with a superlight breaking scale $M_B \lesssim 10^{-6} M_W$ and finally (iii) a composite model⁴⁾ of quarks and leptons with spontaneous B violation. The models (i) and (ii) are similar in character to the works of Refs. 1) and 2). The interest of the model (iii) lies in the fact that baryon number is an "automatic" symmetry, in contrast with models (i) and (ii) where this symmetry arises only when the Higgs Lagrangian is suitably restricted.

2. We now illustrate our ideas using a gauge model based on the group $SU(2)_L \times U(1) \times SU(3)_C$. For simplicity consider only one generation. The fermions are then assigned to the gauge group in the standard manner⁵⁾ as follows:

$$Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} : \left(\frac{1}{2}, \frac{1}{3}, 3 \right); \quad u_R : \left(0, \frac{4}{3}, 3 \right) \\ d_R : \left(0, -\frac{2}{3}, 3 \right) \quad (1)$$

^{*)} In general, one would expect restrictions on the strengths and possibly, the number of the associated zero mass Goldstones from nucleosynthesis.

$$\psi_L = \begin{pmatrix} \nu_L \\ e_L^- \end{pmatrix} : \left(\frac{1}{2}, -1, 1 \right); \quad e_R^- : (0, -2, 1)$$

(1)
cont.

As far as the Higgs sector is concerned, in addition to the standard Higgs doublet (ϕ^+, ϕ^0) behaving as $(1/2, 1, 0)$, we choose the following multiplets^{*)}, 6):

$$\Delta_{ij}^{(1)} : \left(0, \frac{2}{3}, 6 \right)$$

$$\Delta_{ij}^{(2)} : \left(0, -\frac{4}{3}, 6 \right) \quad (2)$$

$$\Delta^{(0)} : (0, 0, 1)$$

We further assign the baryon number, $B_{\Delta(1)} = B_{\Delta(2)} = 2/3$ and $B_{\Delta(0)} = -2$ and choose a Lagrangian which is invariant under $SU(2)_L \times U(1) \times SU(3)_C$ and this $U(1)_B$ symmetry. Complete specification of the model requires new couplings in addition to those present in the standard model:

$$\begin{aligned} \mathcal{L}_Y = & h_d \bar{Q}_L \phi d_R + h_u \bar{Q}_L \tilde{\phi} u_R + h_e \bar{\psi}_L \phi e_R^- \\ & + h_1 \Delta_{ij}^{(1)*} u_{R,i}^T \bar{c}' d_{R,j} + h_2 \Delta_{ij}^{(2)*} d_{R,i}^T \bar{c}' d_{R,j} \quad (3) \\ & + \text{h.c.} \end{aligned}$$

$$\begin{aligned} V = & V_0(\phi, \Delta^{(a)}) + \beta \epsilon_{ijk} \epsilon_{i'j'k'} \Delta_{ii'}^{(1)} \Delta_{jj'}^{(1)} \Delta_{kk'}^{(2)} \Delta_{(4)}^{(0)} \\ & + \text{h.c.} \end{aligned}$$

^{*)} These multiplets are the appropriate subset of the Higgs content of the left-right symmetric model described in Ref. 6).

where

$$V(\phi, \Delta^{(a)}) = \sum_{\substack{H_a = \phi, \Delta^{(0)}, \\ \Delta^{(1)}, \Delta^{(2)}}} \left(-\mu_{H_a}^2 H_a^\dagger H_a + \lambda_{H_a} (H_a^\dagger H_a)^2 \right) \\ + \sum_{H_a = \phi, \Delta^{(0)}, \Delta^{(1)}, \Delta^{(2)}} \lambda_{H_a H_b} (H_a^\dagger H_a) (H_b^\dagger H_b) \quad (5)$$

with

$$\mu_\phi^2, \mu_{\Delta^{(0)}}^2 > 0$$

and

$$\mu_{\Delta^{(1)}}^2, \mu_{\Delta^{(2)}}^2 < 0$$

(6)

The $\mathcal{L}_Y$ and V are invariant under $U(1)_B$. It now follows from Eqs. (5) and (6) that, for a range of the parameters $\lambda_{H_a H_b}$,

$$\langle \phi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

and

$$\langle \Delta^{(0)} \rangle = M_B \quad (7)$$

leading to spontaneous breaking of global baryon number. It is very easy to check¹⁾ that the Goldstone boson corresponding to this symmetry breakdown is given by $(\text{Im} \Delta^{(0)}) \equiv \chi_B$. The second term in Eq. (4) now gives rise to baryon number violating interactions.

It is clear that the massless particle χ_B has no direct coupling to light fermions since it carries $B = 2$. In fact, for large M_B , the χ_B is not part of the low energy effective light particle theory. Therefore, all its couplings to light fermions are suppressed by powers of $(1/M_B)$. The leading light particle - χ_B coupling is given by Fig. 1 and leads to effective neutron-antineutron coupling $\approx N^T C^{-1} \gamma_5 N \chi_B$, where N stands for the neutron field. Its strength $g_{NN\chi}$ is given by

$$g_{NN\chi_B} \simeq h_1^2 h_2 \beta |\psi(0)|^4 / m_{\Delta_{ij}}^6$$

where $\psi(x)$ is the three quark wave function in the nucleon. Correspondingly, there appears a $N-\bar{N}$ oscillation amplitude $\delta m_{N\bar{N}} \approx g_{NN\chi} M_B$, which is bounded from present limits on nuclear stability^{6),7)} to be $\leq 10^{-30}$ GeV. Choosing $m_{\Delta_{ij}} \approx M_B$ as would be expected and $h_1 \approx h_2 \approx \beta \approx 10^{-2}$, we find for the scale of B violation

$$M_B \gtrsim 10^4 \text{ GeV} \quad (8)$$

If we amend the above model by the addition of a right-handed Majorana fermion N_R coupled to left-handed neutrinos ν_L and also include the coupling $N_R^T C^{-1} N_R \Delta^{(0)}$ (allowed by gauge invariance), the global $U(1)$ symmetry becomes associated with $(B-L)$. The massless particle χ_B then also plays the role of the Majoron of Ref. 1).

3. In this section, we present a different gauge model where spontaneous baryon number violation arises from a very low mass scale. The gauge group is still $SU(2)_L \times U(1) \times SU(3)_C$, with fermions and the Higgs doublet ϕ assigned in the same way as in the previous model. For the new Higgs bosons needed to implement spontaneous baryon number violation, we choose:

$$\begin{aligned} \Delta_{ij}^p &= \left(1, \frac{2}{3}, 6\right) \\ \Delta_{\ell\ell}^p &= (1, -2, 1) \end{aligned} \quad (9)$$

(i, j stand for colour indices; $p = 1, 2, 3$ for weak isospin vector). As before, Δ_{ij} have baryon number $2/3$ and $\Delta_{\ell\ell}$ has baryon number -2 . Note further that, in contrast to the model of the previous section, the Δ 's are triplets under $SU(2)_L$.

The new couplings can be written as:

$$\begin{aligned}
 \mathcal{L}'_Y = & h_q Q_{Li}^T C^{-1} \tau_2 \vec{\tau} Q_{Lj} \vec{\Delta}_{ij}^* \\
 & + h_\ell \Psi_L^T C^{-1} \tau_2 \vec{\tau} \Psi_L \vec{\Delta}_{\ell\ell}^* \\
 & + \beta' \epsilon_{ijk} \epsilon_{ij'k'} \Delta_{ii'}^p \Delta_{jj'}^p \Delta_{kk'}^q \Delta_{\ell\ell}^q \\
 & + h.c.
 \end{aligned} \tag{10}$$

In this model, the exact global $U(1)$ symmetry is actually B-L, which is broken by:

$$\langle \Delta_{\ell\ell}^{1+i2} \rangle = K_B \tag{11}$$

As a result, much the same way as in Ref. 6), one obtains the $\Delta B = 2$ and $\Delta L = 2$ selection rules for baryon and lepton violations respectively. However, since $\Delta_{\ell\ell}$ couples to left-handed neutrinos, K_B must be very small²⁾. The light neutrino mass is now given by $h_\ell K_B \lesssim 10$ eV and for $h \approx 10^{-3}$ this implies that $K_B < 10$ keV. It has already been pointed out³⁾, in the context of the model of Ref. 2), that there is a direct coupling of χ_B to the up and down quarks with strength $h (K_B/V)$. This in turn presents a new mechanism for energy loss from red giants⁸⁾ and will disagree with present astrophysical observations unless³⁾ $K_B/V \lesssim 10^{-6}$ or $K_B \lesssim 100$ keV.

We now show that the same low mass scale can also lead to a consistent theory of baryon number violation. The only kind of baryon violation in this model is of $\Delta B = 2$ type and proceeds via the graph in the Figure. In this case, since the largest mass in the theory ≈ 1 TeV, we expect $m_{\Delta_{ij}} \approx 1$ TeV. If we choose $h_q \approx \beta \approx 10^{-3}$ we get a $N^T C^{-1} \gamma_5 N \chi_B$ coupling $g_{NN\chi} \approx 10^{30}$ consistent with observations^{6),7)}.

We now point out an important restriction on this way of breaking global symmetries at very low mass scale. The essential reason for χ_B to couple weakly to fermions is the following: $\Delta_{\ell\ell}$ being an $SU(2)_L$ triplet also contributes a part to the zero mass Higgs-Kibble mode that becomes the longitudinal mode of the neutral gauge boson. This is (apart from normalization) given by:

$$G = V \operatorname{Im} \phi^0 + 2K_B \operatorname{Im} \Delta_{ll}^0 \quad (12)$$

Then if only one Higgs doublet acquires a vacuum expectation value, the orthogonal combination is automatically given by:

$$\chi_B = -2K_B \operatorname{Im} \phi^0 + V \operatorname{Im} \Delta_{ll}^0 \quad (13)$$

Since the fermion couplings of χ_B are generated via the ϕ piece in Eq. (13), such couplings are of order K_B/V relative to the normal standard Higgs couplings and can be made small, by only choosing K_B to be small. If, however, there are more Higgs doublets, the above simple result does not follow in general and additional fine tuning will be required to suppress χ_B couplings to the desired level.

4. The models of Sections 2 and 3 have baryon number as a "natural" but not "automatic"⁹⁾ global symmetry: renormalizable interactions could be added among the various Higgs fields respecting the gauge invariance but not baryon number. Apart from aesthetic considerations, these interactions appear especially dangerous if one takes the point of view that gravity will not respect any of the global symmetries of the "low energy" action. Superrenormalizable B violating interactions could actually be weighted by positive powers of the Planck mass. This is in contrast with the case of an "automatic" global symmetry: still interesting but tiny violating terms could be introduced in the effective action in the form of non-renormalizable interactions weighted by inverse Planck masses¹⁰⁾.

In view of all that, it is interesting to look for an example where B is an automatic global symmetry, which can subsequently be spontaneously broken. Such an example is provided in the context of a composite model of quarks and leptons. This model was recently discussed in Ref. 4) in connection with an understanding of the scale of weak interactions.

We assume there is an unbroken gauge group based on $G_L \equiv SU(4)_H \times SU(3)_C \times U(1)_{em}$. We postulate the existence of two fermionic preons (F_u, F_d) and two scalar preons (ϕ_C, ϕ_ℓ) with a transformation property under G_L as follows:

$$\begin{aligned}
 F_u &: (4, 1, \frac{1}{2}) \\
 F_d &: (4, 1, -\frac{1}{2}) \\
 \text{and} \\
 \phi_c &: (\bar{4}, 3, \frac{1}{6}) \\
 \phi_\ell &: (\bar{4}, 1, -\frac{1}{2})
 \end{aligned} \tag{14}$$

The quarks and leptons which are singlets of the binding hypercolour force, $SU(4)_H$, are denoted by

$$\begin{aligned}
 u &= (F_u \phi_c) & \nu &= (F_u \phi_\ell) \\
 d &= (F_d \phi_c) & e^- &= (F_d \phi_\ell)
 \end{aligned} \tag{15}$$

We assume the hypercolour scale Λ_H to be ≈ 1 TeV and require that any particle not protected by a symmetry to be massless, will have mass $\approx \Lambda_H$. Thus, quarks and leptons will be massless due to the unbroken chiral symmetries in the Lagrangian and any other bound state will have mass $\approx \Lambda_H$. We then argue that quark and lepton masses arise from a tiny $SU(4)_H$ invariant mass term added to the basic Lagrangian.

At the preon level the model has a $U(1)^3$ global symmetry associated with fermion number, ϕ_c number and ϕ_ℓ number. The only gauge invariant renormalizable interaction breaking part of this symmetry is

$$\lambda \epsilon_{ijkm} \epsilon_{\alpha\beta\gamma} \phi_{ci}^\alpha \phi_{ej}^\beta \phi_{ck}^\gamma \phi_{\ell m} \tag{16}$$

$$\alpha, \beta, \gamma \equiv 1, 2, 3$$

$$i, j, k, m = 1, 2, 3, 4$$

In this way one is left with a $U(1)^2$ symmetry which can be taken as generating baryon and lepton numbers.

To understand in the model the small neutrino mass, it is necessary to postulate⁴⁾ a condensate

$$\langle \nu_R^T C^{-1} \nu_R \rangle \equiv M_1^3 \quad (17)$$

breaking lepton number and leading to a massless two neutrino composite Majoron. We point out here that it is also possible to break the residual $U(1)_B$ by vacuum condensation, thereby giving another invisible Goldstone boson. We do this by allowing for the formation of the following $SU(4)_H$ singlet condensate^{*)}:

$$\langle F_u F_u F_u F_u F_d F_d F_d F_d \rangle \equiv M_2^{12} \quad (18)$$

The minimal diagram leading to baryon number violation at the composite level involves two powers of the coupling λ in Eq. (16) and one power of the condensates in Eqs. (17) and (18). A crude estimate for the six quark $\Delta B = 2$ coupling f is:

$$f \simeq \lambda^2 \left(\frac{M_2}{\Lambda_H} \right)^{12} \left(\frac{M_1}{\Lambda_H} \right)^3 \frac{1}{\Lambda_H^5} \quad (19)$$

If we choose $M_1, M_2 \simeq \Lambda_H/5$, $\Lambda_H \simeq 1$ TeV and $\lambda \simeq 10^{-3}$, we get $\delta m_{NN} \simeq 10^{-30}$ GeV. An important point is that we did not have to choose $M_{1,2}$ too different from the scale Λ_H , thus leaving open the possibility that all the new dynamical scales M_i owe their origin to the scale Λ_H . Needless to say that one could view the first model of this paper as an effective Lagrangian version of a composite model of this type.

^{*)} Strictly speaking, the smallest condensate allowed by $SU(4)_H$ invariance considerations is the four-preon condensate $\langle F_u F_u F_d F_d \rangle$; but this would lead to very fast proton decay. We therefore assume that the only condensate that forms is of the eight-fermion type. Eight-fermion condensates would, however, be more natural in a two-generation generalization of the model, when the hyper-colour group becomes $SU(8)_H$ instead of $SU(4)_H$ to satisfy 't Hooft anomalies⁴⁾.

In conclusion, we have presented various examples of consistent and realistic gauge models, where global baryon number symmetry can be spontaneously broken at relatively low energy. The associated Goldstone boson, like the Majoron, is invisible. Going from the standard "elementary" to a composite model for quarks and leptons has enabled us to have baryon number as an "automatic" global symmetry and, at the same time, has provided forces that could give rise to its breaking through vacuum condensation.

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FIGURE CAPTION

Feynman diagram for the $\Delta B = 2$ type coupling of χ_B . Replacing the χ_B -leg
by a $\langle \Delta^{(0)} \rangle$ leads to the $N-\bar{N}$ transition amplitude.