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Unification and local baryon number

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ABSTRACT

We investigate the possibility to find an ultraviolet completion of the simple extensions of the Standard Model where baryon number is a local symmetry. In the context of such theories one can understand the spontaneous breaking of baryon number at the low scale and the proton stability. We find a simple theory based on $SU(4)_C \otimes SU(3)_L \otimes SU(3)_R$ where baryon number is embedded in a non-Abelian gauge symmetry. We discuss the main features of the theory and the possible implications for experiments. This theory predicts stable colored and/or fractional electric charged fields which can give rise to very exotic signatures at the Large Hadron Collider experiments such as CMS and ATLAS. We further discuss the embedding in a gauge theory based on $SU(4)_C \otimes SU(4)_L \otimes SU(4)_R$ which could define the way to achieve the unification of the gauge interactions at the low scale.

1. Introduction

The Standard Model (SM) of particle physics is today a very successful theory of nature which describes most of the experimental results below or at the electroweak scale, $\Lambda_W \sim 100$ GeV. There are many appealing ideas for physics beyond the Standard Model. In the context of grand unified theories one can understand why the weak, the electromagnetic and strong interactions are so different. In this context the SM interactions are just different manifestations of the same fundamental interaction [1]. The idea of grand unification is very appealing but unfortunately these theories can be realized only at the high energy scale, $M_{GUT} \approx 10^{14-16}$ GeV, in agreement with evolution of the gauge couplings [2] and the proton decay experimental bounds [3]. It is difficult to imagine a direct test of these theories at colliders due to the fact that they can only be realized at energy scales much larger than the center-of-mass energy of any future collider experiment.

Recently, several effective field theories have been proposed in order to understand the possible absolute stability of the proton [4–8]. In this context the global baryon number symmetry present in the SM is promoted to be a local gauge symmetry which is spontaneously broken at the low scale. Since in this context baryon number is not broken in one unit these theories predict that the proton is stable. Therefore, these theories provide an ideal framework to investigate the unification of fundamental forces at scales much smaller than the standard grand unified scale. See Refs. [9–12] for different studies in the context of these theories. In Ref. [10] we have investigated the unification of gauge interactions from the bottom-up approach in order to understand the different scenarios where the unification can be realized at the low scale in agreement with the experiment.

In this article we investigate simple unified theories which are the ultraviolet completion of the theories proposed in Refs. [4–7] and can be realized at the low scale. These theories are crucial to understand the possibility to define a grand unified theory where the baryon number is a local symmetry and the proton is stable. In this way one can hope to have a realistic theory for the unification of gauge interactions at the low scale. We focus mainly on a simple theory based on $SU(4)_C \otimes SU(3)_L \otimes SU(3)_R$ where baryon number is embedded in a non-Abelian gauge symmetry. In this context the color and the baryon number are unified in the $SU(4)_C$ symmetry. We discuss the main features of the theory and the possible implications for experiments. This theory predicts stable colored and/or fractional electric charged fields which can give rise to very exotic signatures at the Large Hadron Collider experiments such as CMS and ATLAS. We also discuss the embedding in a gauge theory based on $SU(4)_C \otimes SU(4)_L \otimes SU(4)_R$ which could define the way to achieve the unification of the gauge interactions at the low scale since the proton is absolutely stable in this context.

2. Theories for baryon number

The idea of investigating a theory where the baryon number is defined as a local symmetry was discussed in Refs. [13,14]. See also

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Refs. [15–17] for previous studies. In Refs. [4–7] we have proposed several theories where the gauge symmetry is the SM gauge symmetry and a local Abelian symmetry $U(1)_B$. These theories have the common features:

- The local baryon number can be spontaneously broken at the low scale.
- The proton can be absolute stable in the simplest models.
- In order to define an anomaly free theory one needs to introduce extra vector-like fermions with different baryon numbers.
- In this context one predicts the existence of a leptophobic gauge boson, Z_B, which couples only to the SM quarks and the new vector-like fermions.
- These theories predict generically a cold dark matter candidate which is the lightest neutral field in the new sector of the theory.
- One typically has a relation between the matter–antimatter and the dark matter asymmetries.

Clearly, these effective theories can provide an ideal framework to understand the unification of interactions at the low scale. In this article we propose a new theory which can help us to understand this possibility.

3. Towards unification

In the previous section, we have discussed the theories where baryon number is a local symmetry. Typically, in an unified theory where quarks and leptons live in the same multiplet one cannot define B and L for the matter multiplets. However, if one has extra matter one can have matter multiplets with definite baryon number and one of the generators in the algebra can be identified as baryon number generator. One example has been discussed in Ref. [18] where following the old idea of Pati–Salam [19] and the model proposed in Ref. [20], $U(1)_B$ lives inside $SU(4)_C$. This idea is not new but it is the key to find a new simple unified theory where the baryon number is a local symmetry. The model proposed in Ref. [18] is simple but one cannot realize the breaking of the gauge symmetry to the SM model plus the local gauge symmetry $U(1)_B$ and the proton is not stable. One also has an Abelian gauge symmetry as in the SM.

In this section, we show that it is possible to use the idea of trinification to motivate a simple theory where baryon number is a local symmetry. We therefore consider the gauge group

$$G_{433} = SU(4)_C \otimes SU(3)_L \otimes SU(3)_R\,, \tag{1}$$

with the Standard Model fermions embedded in

$$Q \sim (4, \bar{3}, 1)\,, \quad Q^c \sim (\bar{4}, 1, 3)\,, \text{and} \quad L \sim (1, 3, \bar{3})\,. \tag{2}$$

Anomaly cancellation requires that we introduce the extra fields

$$\Psi^c \sim (1, 3, 1) \quad \text{and} \quad \eta \sim (1, 1, \bar{3})\,. \tag{3}$$

Let us discuss the explicit form of all matter multiplets:

- The left-handed SM quarks live in the Q multiplet (one for each family) together with extra colorless fields with baryon number as we show here

$$Q = \begin{pmatrix} d_r & u_r & D_r \\ d_b & u_b & D_b \\ d_g & u_g & D_g \\ \Psi_d & \Psi_u & \Psi_D \end{pmatrix} = \begin{pmatrix} q \\ \Psi \end{pmatrix}. \tag{4}$$

  Here q is the quark multiplet used in trinification, which is the theory based on $SU(3)_C \otimes SU(3)_L \otimes SU(3)_R$ and Ψ is a vector containing the extra fields Ψ_d, Ψ_u and Ψ_D. The indices r, b and g correspond to the different colors.

- The right-handed SM quarks live in the Q^c multiplet together with the partners of the extra fields in Q

$$Q^c = \begin{pmatrix} d^c_{\bar{r}} & d^c_{\bar{b}} & d^c_{\bar{g}} & \eta^c_d \\ u^c_{\bar{r}} & u^c_{\bar{b}} & u^c_{\bar{g}} & \eta^c_u \\ D^c_{\bar{r}} & D^c_{\bar{b}} & D^c_{\bar{g}} & \eta^c_D \end{pmatrix} = \begin{pmatrix} q^c & \eta^c \end{pmatrix}, \tag{5}$$

- The SM leptons live in the L multiplet together with extra heavy leptons as in the case of trinification

$$L = \begin{pmatrix} N_1 & E^+ & \nu \\ E^- & N_2 & e^- \\ \nu^c & e^+ & N_3 \end{pmatrix}, \tag{6}$$

- As we have mentioned, here one needs the extra fermions Ψ^c and η to cancel all the anomalies. They are given by

$$\Psi^c = \begin{pmatrix} \Psi^c_d & \Psi^c_u & \Psi^c_D \end{pmatrix} \quad \text{and} \quad \eta = \begin{pmatrix} \eta_d \\ \eta_u \\ \eta_D \end{pmatrix}. \tag{7}$$

This theory has many interesting features:

- The decay of the proton could happen if the dimension nine operators, such as $Q\,Q\,Q\,L\Phi\Phi\phi^\dagger/\Lambda^5$, are present. Therefore, the scale Λ can be small. Here $\Phi \sim (1, 3, \bar{3})$ is the scalar field present in trinification. See the next sections for details.
- In the limit $v_B \to \infty$ the new fermions decouple and we are left with the known trinification model based on the $SU(3)_C \otimes SU(3)_L \otimes SU(3)_R$ gauge symmetry.
- In the leptonic multiplet L the leptons and anti-leptons are unified in the same representation. Therefore, the total lepton number is broken explicitly in this theory.
- This theory predicts the existence of new vector-like quarks, $D + D^c$, with electric charge $-1/3$, new extra neutral leptons N_1, N_2, N_3 and the right-handed neutrinos ν^c. We also find new vector-like heavy leptons E^+ and E^- as in trinification.
- There are exotic fields with fractional charge as well, the fields Ψ, Ψ^c, η and η^c. The electric charges are given by

$$\begin{aligned} &Q\,(\Psi_u) = +2/3\,, \, Q\,(\Psi_d) = Q\,(\Psi_D) = -1/3, \\ &Q\,(\Psi^c_u) = -2/3\,, \, Q\,(\Psi^c_d) = Q\,(\Psi^c_D) = +1/3, \\ &Q\,(\eta_u) = +2/3\,, \, Q\,(\eta_d) = Q\,(\eta_D) = -1/3, \\ &Q\,(\eta^c_u) = -2/3\,, \, Q\,(\eta^c_d) = Q\,(\eta^c_D) = +1/3\,. \end{aligned}$$

3.1. Symmetry breaking

The gauge symmetry $SU(4)_C \otimes SU(3)_L \otimes SU(3)_R$ can be broken in two steps:

- $SU(4)_C$ breaks down to $SU(3)_C \otimes U(1)_B$ once the Higgs $\Sigma \sim (15, 1, 1)$ acquires a vacuum expectation value in the T^{15}_C direction, $\langle\Sigma\rangle = v_C\, T^{15}_C$, here $T^{15}_C = \text{diag}(1, 1, 1, -3)/2\sqrt{6}$. Therefore, one obtains a low energy theory based on trinification and the local baryon number, i.e. $SU(3)_C \otimes SU(3)_L \otimes SU(3)_R \otimes U(1)_B$. The Baryon number generator will be

$$Y_B = 2\sqrt{\frac{2}{3}}\,T^{15}_C\,. \tag{8}$$

- The $U(1)_B$ gauge boson must acquire mass. We achieve it adding a new Higgs, $\phi \sim (4, 1, 1)$ which vacuum expectation value breaks the local baryon number. The explicit form of the ϕ field is given by $\phi^T = (\phi_r\ \phi_b\ \phi_g\ S_B)$ and the VEV of S_B is $v_B/\sqrt{2}$ in our notation.