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Neutral $SU(2)$ gauge extension of the standard model and a vector-boson dark-matter candidate

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ABSTRACT

If the standard model of particle interactions is extended to include a neutral $SU(2)_N$ gauge factor, with $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_N$ embedded in E_6 or $[SU(3)]^3$, a conserved generalized R parity may appear. As a result, apart from the recent postulate of a separate non-Abelian gauge factor in the hidden sector, we have the first example of a possible dark-matter candidate X_1 which is a non-Abelian vector boson coming from a *known* unified model. Using current data, its mass is predicted to be less than about 1 TeV. The associated Z' of this model, as well as some signatures of the Higgs sector, should then be observable at the LHC (Large Hadron Collider).

1. Introduction

Whereas dark matter [1] is generally accepted as being an important component of the Universe, its nature remains unclear. Myriad hypotheses exist, but so far, almost all particles which have been considered as dark-matter candidates are spin-zero scalars, or spin-one-half fermions, or a combination of both [2]. Spin-one Abelian vector bosons are also possible, but only in the context of more exotic scenarios, such as those of universal extra dimensions [3] and little Higgs models [4]. Spin-one non-Abelian vector bosons from a hidden sector have also been considered [5–7]. In this Letter, we will show for the first time that a spin-one non-Abelian vector boson which interacts directly with known quarks and leptons may also be a dark-matter candidate, motivated by an extension of the standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge model of particle interactions with an extra neutral $SU(2)_N$ gauge factor, which is derivable from a decomposition of E_6 or $[SU(3)]^3$.

We will show how a conserved generalized lepton number may be defined, in analogy with the previously proposed dark left–right gauge models [8–12]. The difference is that the vector bosons corresponding to $W_R^{\pm}$ are now *electrically neutral* and may become dark-matter candidates. We will also show how the decomposition of E_6 or $[SU(3)]^3$ leads to three different models of the form $SU(3)_C \times SU(2)_L \times SU(2)' \times U(1)'$. The first is the conventional left–right model where $SU(2)' = SU(2)_R$ and $U(1)' = U(1)_{B-L}$, the second is the alternative left–right model [13], and the third is the case [14] where $U(1)' = U(1)_Y$ and $SU(2)' = SU(2)_N$, with some of its Z' phenomenology already discussed [15]. We do not use the original notation of $SU(2)_I$, where the subscript I stands for "inert", because this new gauge group certainly has *interactions* linking the known quarks and leptons with the exotic fermions.

We will discuss the phenomenology of this model, assuming that the real vector gauge boson X_1 of $SU(2)_N$ is the lightest particle of odd R parity, where $R = (-1)^{3B+L+2j}$, to account for the dark-matter relic abundance of the Universe. This is a new and important possibility not discussed previously in the applications of this model. Combining it with the recent CDMS data [16], we find m_X to be less than about 1 TeV. This means that the associated $Z'(= X_3)$ boson (with even R parity) should not be much heavier, and be observable at the Large Hadron Collider (LHC). The Higgs sector of this model also has some salient characteristics, with good signatures at the LHC. Note that our proposal is very different from the hidden-sector case, where all three gauge bosons, i.e. $X_{1,2,3}$, would all be dark-matter candidates having the same mass.

2. Model

Under $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_N$, where $Q = T_{3L} + Y$, the fermion content of this nonsupersymmetric model is given by

$$\begin{pmatrix} u \\ d \end{pmatrix} \sim (3, 2, 1/6; 1), \qquad u^c \sim \left(3^*, 1, -2/3; 1\right), \tag{1}$$

$$\left(h^c, d^c\right) \sim \left(3^*, 1, 1/3; 2\right), \qquad h \sim (3, 1, -1/3; 1), \tag{2}$$

$$\begin{pmatrix} N & \nu \\ E & e \end{pmatrix} \sim (1, 2, -1/2; 2), \qquad \begin{pmatrix} E^c \\ N^c \end{pmatrix} \sim (1, 2, 1/2; 1), \tag{3}$$

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$$e^c \sim (1,1,1;1), \qquad (\nu^c, n^c) \sim (1,1,0;2), \tag{4}$$

where all fields are left-handed. The $SU(2)_L$ doublet assignments are vertical with $T_{3L} = \pm 1/2$ for the upper (lower) entries. The $SU(2)_N$ doublet assignments are horizontal with $T_{3N} = \pm 1/2$ for the right (left) entries. There are three copies of the above to accommodate the known three generations of quarks and leptons, together with their exotic counterparts. It is easy to check that all anomalies are canceled.

Consider a Higgs sector of one bidoublet and two doublets:

$$\begin{pmatrix} \phi_1^0 & \phi_2^0 \\ \phi_1^- & \phi_2^- \end{pmatrix} \sim (1,2,-1/2;2), \qquad \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix} \sim (1,2,1/2;1),$$
$$(\chi_1^0, \chi_2^0) \sim (1,1,0;2). \tag{5}$$

The allowed Yukawa couplings are thus

$$(d\phi_1^0 - u\phi_1^-)d^c - (d\phi_2^0 - u\phi_2^-)h^c, \qquad (u\eta^0 - d\eta^+)u^c,$$
$$(h^c\chi_2^0 - d^c\chi_1^0)h, \tag{6}$$
$$(N\phi_2^- - \nu\phi_1^- - E\phi_2^0 + e\phi_1^0)e^c,$$
$$(E\eta^+ - N\eta^0)n^c - (e\eta^+ - \nu\eta^0)\nu^c, \tag{7}$$
$$(EE^c - NN^c)\chi_2^0 - (eE^c - \nu N^c)\chi_1^0, \tag{8}$$

as well as

$$(EE^c - NN^c)\bar{\chi}_1^0 + (eE^c - \nu N^c)\bar{\chi}_2^0. \tag{9}$$

If Eq. (9) is disallowed, then a generalized lepton number may be defined, with the assignments

$$L = 0: \quad u, d, N, E, \phi_1, \eta, \chi_2^0, n^c, \qquad L = 1: \quad \nu, e, h, \phi_2,$$
$$L = -1: \quad \chi_1^0, \tag{10}$$

so that the neutral vector gauge boson X linking E to e has $L = 1$. In this scenario, ϕ_2^0 and χ_1^0 cannot have vacuum expectation values. Fermion masses are obtained from the other neutral scalar fields as follows: m_d, m_e from $\langle\phi_1^0\rangle = v_1$; m_u, m_ν from $\langle\eta^0\rangle = v_3$; m_h, m_E, m_N from $\langle\chi_2^0\rangle = u_2$. Actually, because of the Nn^c mass term from v_3, N pairs up with a linear combination of N^c and n^c to form a Dirac fermion, leaving the orthogonal combination massless. We will return to the resolution of this problem in a later section.

To forbid Eq. (9), an additional global $U(1)$ symmetry S is imposed, as discussed in the two original dark left–right models [8,11], where $S = L \pm T_{3R}$. Here we have $S = L - T_{3N}$ instead. An alternative solution is to make the model supersymmetric, in which case Eq. (9) is also forbidden. We note that the structure of this model guarantees the absence of flavor-changing neutral currents, allowing thus $SU(2)_N$ to be broken at the relatively low scale of 1 TeV.

3. E_6 origin

As listed in Eqs. (1)–(4), there are 27 chiral fermion fields per generation in this model. This number is not an accident, because it comes from the fundamental representation of E_6 or $[SU(3)]^3 = SU(3)_C \times SU(3)_L \times SU(3)_R$. Under the latter which is the maximal subgroup of the former, these fields transform as $(3,3^*,1) + (1,3,3^*) + (3^*,1,3)$, i.e.

$$\begin{pmatrix} d & u & h \\ d & u & h \\ d & u & h \end{pmatrix} + \begin{pmatrix} N & E^c & \nu \\ E & N^c & e \\ \nu^c & e^c & n^c \end{pmatrix} + \begin{pmatrix} d^c & d^c & d^c \\ u^c & u^c & u^c \\ h^c & h^c & h^c \end{pmatrix}. \tag{11}$$

The decomposition of $SU(3)_L \to SU(2)_L \times U(1)_{Y_L}$ is completely fixed because of the standard model. However, the decomposition of $SU(3)_R \to SU(2)' \times U(1)'$ is not. If we choose the conventional path, then we see from the above that (ν^c, e^c) and (u^c, d^c) are $SU(2)_R$ doublets. However, another choice is to switch the first and third columns of $(1,3,3^*)$ and the first and third rows of $(3^*,1,3)$, i.e.

$$\begin{pmatrix} d & u & h \\ d & u & h \\ d & u & h \end{pmatrix} + \begin{pmatrix} \nu & E^c & N \\ e & N^c & E \\ n^c & e^c & \nu^c \end{pmatrix} + \begin{pmatrix} h^c & h^c & h^c \\ u^c & u^c & u^c \\ d^c & d^c & d^c \end{pmatrix}. \tag{12}$$

This is the alternative left–right model [13], where (n^c, e^c) and (u^c, h^c) are $SU(2)_R$ doublets.

The third choice [14] is to switch the second and third columns of $(1,3,3^*)$ and the second and third rows of $(3^*,1,3)$, i.e.

$$\begin{pmatrix} d & u & h \\ d & u & h \\ d & u & h \end{pmatrix} + \begin{pmatrix} N & \nu & E^c \\ E & e & N^c \\ \nu^c & n^c & e^c \end{pmatrix} + \begin{pmatrix} d^c & d^c & d^c \\ h^c & h^c & h^c \\ u^c & u^c & u^c \end{pmatrix}. \tag{13}$$

This then results in Eqs. (1)–(4).

In analyzing Z' models from E_6, the usual convention is to define the two possible extra $U(1)$ gauge factors as coming from $E_6 \to SO(10) \times U(1)_\psi$ and $SO(10) \to SU(5) \times U(1)_\chi$. The special case $U(1)_\eta = \sqrt{3/8}U(1)_\chi - \sqrt{5/8}U(1)_\psi$ is often also considered. Here the Z' of $SU(2)_N$ couples to the orthogonal combination, i.e. $\sqrt{5/8}U(1)_\chi + \sqrt{3/8}\,U(1)_\psi$. Under the conventional $SU(3)_R$ assignments, this is equivalent to $(1/2)T_{3R} - (3/2)Y_R$, hence n^c is +1/2 and ν^c is $-1/2$ as expected.

4. Gauge boson masses

The extra gauge symmetry $SU(2)_N$ is completely broken by $\langle\chi_2^0\rangle = u_2$, so that each of the three gauge bosons $X_{1,2,3}$ has the same mass, i.e. $m_X^2 = (1/2)g_N^2 u_2^2$. Whereas X_3 should be identified with the extra Z' of this model, coupling to fermions according to T_{3N}, $(X_1 \mp iX_2)/\sqrt{2}$ are the neutral analogs of $W_R^\pm$ with $L = \pm 1$.

With the Higgs content of Eq. (5), there is a massless fermion per generation, corresponding to a linear combination of n^c and N^c. At the same time, the neutrino has only a Dirac mass, from the pairing of ν with ν^c. Consider then the addition of the scalar triplet

$$(\xi_3^0, \xi_4^0, \xi_5^0) \sim (1,1,0;3), \tag{14}$$

with $S = 1$, so that ξ_3^0 couples to $n^c n^c$ and ξ_5^0 couples to $\nu^c\nu^c$. Let these have nonzero vacuum expectation values u_3 and u_5 respectively, then L is broken by the latter to $(-1)^L$ so that ν gets a seesaw Majorana mass in the usual way. There is also a large Majorana mass for n^c, so that no massless particle remains. At the same time, R parity, i.e. $R = (-1)^{3B+L+2j}$, remains valid. All standard-model particles have even R. New particles of even R are ϕ_1, η, χ_2^0, Z'; those of odd R are N, E, n^c, h, ϕ_2, χ_1^0, $X_{1,2}$, the lightest of which is stable and a good dark-matter candidate if it is also neutral. However, N and ϕ_2^0 are ruled out by direct-search experiments because they have Z interactions; n^c and χ_1^0 are also ruled out because they are mass partners of N and ϕ_2^0. That leaves only $X_{1,2}$.

The masses of the gauge bosons are now given by

$$m_W^2 = \frac{1}{2}g_2^2(v_1^2 + v_3^2), \qquad m_{X_{1,2}}^2 = \frac{1}{2}g_N^2\left[u_2^2 + 2(u_3 \mp u_5)^2\right], \tag{15}$$

$$m_{Z,Z'}^2 = \frac{1}{2}\begin{pmatrix} (g_1^2 + g_2^2)(v_1^2 + v_3^2) & -g_N\sqrt{g_1^2 + g_2^2}v_1^2 \\ -g_N\sqrt{g_1^2 + g_2^2}v_1^2 & g_N^2[u_2^2 + v_1^2 + 4(u_3^2 + u_5^2)] \end{pmatrix}. \tag{16}$$