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Generalized lepton number and dark left-right gauge model

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In a left-right gauge model of particle interactions, the left-handed fermion doublet $(\nu, e)_L$ is connected to its right-handed counterpart $(n, e)_R$ through a scalar bidoublet so that e_L pairs with e_R, and ν_L with n_R to form mass terms. Suppose the latter link is severed without affecting the former, then n_R is not the mass partner of ν_L, and as we show in this paper, becomes a candidate for dark matter which is relevant for the recent PAMELA and ATIC observations. We accomplish this in a specific nonsupersymmetric model, where a generalized lepton number can be defined, so that n_R and $W_R^\pm$ are odd under $R \equiv (-1)^{3B+L+2j}$. Fermionic leptoquarks are also predicted.

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I. INTRODUCTION

It was recognized 22 years ago [1,2] that an unconventional left-right gauge extension of the standard model (SM) of particle interactions is possible, with a number of desirable properties. This has become known in the literature as the alternative left-right model (ALRM) [3]. It differs from the conventional left-right model (LRM) [4] in that tree-level flavor-changing neutral currents are naturally absent so that the $SU(2)_R$ breaking scale may be easily below a TeV, allowing both the charged $W_R^\pm$ and the extra neutral Z' gauge bosons to be observable at the large hadron collider (LHC). In this paper, we propose a new variant of this extension which we call the dark left-right model (DLRM). It predicts the *parallel* existence of neutrinos and *scotinos*, i.e. fermionic dark-matter candidates, as explained below.

II. MODEL

Consider the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$. The conventional leptonic assignments are $\psi_L = (\nu, e)_L \sim (1, 2, 1, -1/2)$ and $\psi_R = (\nu, e)_R \sim (1, 1, 2, -1/2)$. Hence ν and e obtain Dirac masses through the Yukawa terms $\bar{\psi}_L \Phi \psi_R$ and $\bar{\psi}_L \tilde{\Phi} \psi_R$, where $\Phi = (\phi_1^0, \phi_1^-; \phi_2^+, \phi_2^0) \sim (1, 2, 2, 0)$ is a Higgs bidoublet and $\tilde{\Phi} = \sigma_2 \Phi^* \sigma_2 = (\bar{\phi}_2^0, -\phi_2^-; -\phi_1^+, \bar{\phi}_1^0)$ transforms in the same way. Both $\langle \phi_1^0 \rangle$ and $\langle \phi_2^0 \rangle$ contribute to m_ν and m_e, and similarly m_u and m_d in the quark sector, resulting thus in the appearance of tree-level flavor-changing neutral currents [5].

Suppose the term $\bar{\psi}_L \tilde{\Phi} \psi_R$ is forbidden by a symmetry, then the same symmetry may be used to maintain $\langle \phi_1^0 \rangle = 0$ and only e gets a mass through $\langle \phi_2^0 \rangle \neq 0$. At the same time, ν_L and ν_R are not Dirac mass partners, and since they are neutral, they can in fact be completely different particles with independent masses of their own. Whereas ν_L is clearly the neutrino we observe in the usual weak interactions, ν_R can now be something else entirely. Here we rename ν_R as n_R and show that it may in fact be a *scotino*, i.e. a fermionic dark-matter candidate.

We impose a new global U(1) symmetry S in such a way that the spontaneous breaking of $SU(2)_R \times S$ will leave the combination $L = S - T_{3R}$ unbroken. We then show that L is a generalized lepton number, with $L = 1$ for the known leptons, and $L = 0$ for all known particles which are not leptons. Our model is nonsupersymmetric, but it may be rendered supersymmetric by the usual procedure which takes the SM to the MSSM (minimal supersymmetric standard model). Under $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1) \times S$, the fermions transform as shown in Table I. Note the necessary appearance of the exotic quark h, which will turn out to carry lepton number as well.

The scalar sector consists of one bidoublet and two doublets:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \qquad \Phi_L = \begin{pmatrix} \phi_L^+ \\ \phi_L^0 \end{pmatrix}, \qquad \Phi_R = \begin{pmatrix} \phi_R^+ \\ \phi_R^0 \end{pmatrix}, \tag{1}$$

as well as two triplets for making ν and n massive separately:

$$\Delta_L = \begin{pmatrix} \Delta_L^+/\sqrt{2} & \Delta_L^{++} \\ \Delta_L^0 & -\Delta_L^+/\sqrt{2} \end{pmatrix}, \quad \Delta_R = \begin{pmatrix} \Delta_R^+/\sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+/\sqrt{2} \end{pmatrix}. \tag{2}$$

Their assignments under S are listed in Table II.

TABLE I. Fermion content of proposed model.

Fermion	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$	S
$\psi_L = (\nu, e)_L$	(1, 2, 1, − 1/2)	1
$\psi_R = (n, e)_R$	(1, 1, 2, −1/2)	1/2
$Q_L = (u, d)_L$	(3, 2, 1, 1/6)	0
$Q_R = (u, h)_R$	(3, 1, 2, 1/6)	1/2
d_R	(3, 1, 1, − 1/3)	0
h_L	(3, 1, 1, − 1/3)	1

TABLE II. Scalar content of proposed model.

Scalar	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$	S
Φ	(1, 2, 2, 0)	1/2
$\tilde{\Phi} = \sigma_2 \Phi^* \sigma_2$	(1, 2, 2, 0)	$-1/2$
Φ_L	(1, 2, 1,1/2)	0
Φ_R	(1, 1, 2,1/2)	$-1/2$
Δ_L	(1, 3, 1, 1)	-2
Δ_R	(1, 1, 3, 1)	-1

The Yukawa terms allowed by S are then $\bar{\psi}_L \Phi \psi_R$, $\bar{Q}_L \tilde{\Phi} Q_R$, $\bar{Q}_L \Phi_L d_R$, $\bar{Q}_R \Phi_R h_L$, $\psi_L \psi_L \Delta_L$, and $\psi_R \psi_R \Delta_R$, whereas $\bar{\psi}_L \tilde{\Phi} \psi_R$, $\bar{Q}_L \Phi Q_R$, and $\bar{h}_L d_R$ are forbidden. Hence m_e, m_u come from $v_2 = \langle \phi_2^0 \rangle$, m_d comes from $v_3 = \langle \phi_L^0 \rangle$, m_h comes from $v_4 = \langle \phi_R^0 \rangle$, m_ν comes from $v_5 = \langle \Delta_L^0 \rangle$, and m_n comes from $v_6 = \langle \Delta_R^0 \rangle$. This structure shows clearly that flavor-changing neutral currents are guaranteed to be absent at tree level.

III. HIGGS STRUCTURE

We now show that $v_1 = \langle \phi_1^0 \rangle = 0$ is a solution of the Higgs potential which leaves the combination $L = S - T_{3R}$ unbroken, even as $SU(2)_L \times SU(2)_R \times U(1) \times S$ is broken all the way down to $U(1)_{\rm em}$. The generalized lepton number L remains 1 for ν and e, and 0 for u and d, but the new particle n has $L = 0$ and h has $L = 1$, whereas $W_R^\pm$ has $L = \mp 1$ and Z' has $L = 0$, etc. As neutrinos acquire Majorana masses, L is broken to $(-)^L$. The generalized R parity is then defined in the usual way, i.e. $(-)^{3B+L+2j}$. The known quarks and leptons have even R, but n, h, $W_R^\pm$, and $\Delta_R^\pm$ have odd R. Hence the lightest n can be a viable dark-matter candidate if it is also the lightest among all the particles having odd R. Note that R parity has now been implemented in a *nonsupersymmetric* model.

The Higgs potential of Φ, Φ_L, Φ_R, Δ_L, and Δ_R consists of many terms. Considered as a function of their vacuum expectation values, its minimum is of the form

$$V = \sum_i m_i^2 v_i^2 + \frac{1}{2}\sum_{i,j} \lambda_{ij} v_i^2 v_j^2 + 2\mu_R v_4^2 v_6 + 2\mu_2 v_2 v_3 v_4 + 2\lambda' v_1^2 v_5 v_6. \quad (3)$$

The last three terms of V come from the allowed terms $\Phi_R^\dagger \Delta_R \tilde{\Phi}_R$, $\Phi_L^\dagger \Phi \Phi_R$, and $\mathrm{Tr}(\tilde{\Phi}^\dagger \Delta_L \Phi \Delta_R^\dagger)$, whereas the terms $\mathrm{Tr}(\Phi \tilde{\Phi}^\dagger)$ $(v_1 v_2)$, $\Phi_L^\dagger \tilde{\Phi} \Phi_R$ $(v_1 v_3 v_4)$, $\Phi_L^\dagger \Phi \tilde{\Phi}^\dagger \Phi_L$ $(v_1 v_2 v_3^2)$, $\Phi_R^\dagger \Phi^\dagger \tilde{\Phi} \Phi_R$ $(v_1 v_2 v_4^2)$, $\mathrm{Tr}(\Phi^\dagger \Delta_L \tilde{\Phi} \Delta_R^\dagger)$ $(v_2^2 v_5 v_6)$, and $\mathrm{Tr}(\Phi^\dagger \Delta_L \Phi \Delta_R^\dagger)$ $(v_1 v_2 v_5 v_6)$ are all forbidden. From the conditions $\partial V/\partial v_i = 0$, it is clear that a solution exists for which $v_1 = 0$ because V is a function of v_1^2 only, even if all other v_i's are nonzero, provided of course that $\partial^2 V/\partial v_1^2 > 0$ which is satisfied for a range of values in parameter space. It also shows that the only residual global symmetry of V is L.

The breaking of $SU(2)_R \times U(1) \times S$ to $U(1)_Y \times L$ is accomplished by $v_4 \neq 0$ and $v_6 \neq 0$. Note here that ϕ_R^0 has $L = -1/2 - (-1/2) = 0$ and Δ_R^0 has $L = -1 - (-1) = 0$. The subsequent breaking of $SU(2)_L \times U(1)_Y$ to $U(1)_{\rm em}$ occurs through $v_2 \neq 0$ and $v_3 \neq 0$. Note here that ϕ_2^0 has $L = 1/2 - 1/2 = 0$ and ϕ_L^0 has $L = 0 - 0 = 0$. At this stage, neutrinos are massless because $v_5 = 0$ is protected by L. We now add the dimension-three soft term $\mu_L \tilde{\Phi}_L^\dagger \Delta_L \Phi_L$ which breaks L explicitly by two units, so that a small $v_5 \simeq -\mu_L v_3^2/m_5^2$ is induced [6] and neutrinos acquire mass. Here μ_L may be naturally small because it breaks L to $(-)^L$. Note that n becomes massive in an exactly parallel way through v_6 but without breaking lepton number. Note also that the observed baryon asymmetry of the Universe is obtainable through leptogenesis from Δ_L decay [6].

IV. GAUGE SECTOR

Since e has $L = 1$ and n has $L = 0$, the W_R^+ of this model must have $L = S - T_{3R} = 0 - 1 = -1$. This also means that unlike the conventional LRM, $W_R^\pm$ does not mix with the $W_L^\pm$ of the SM at all. This important property allows the $SU(2)_R$ breaking scale to be much lower than it would be otherwise, as explained already 22 years ago [1,2]. Assuming that $g_L = g_R$ and let $x \equiv \sin^2\theta_W$, then the neutral gauge bosons of the DLRM (as well as the ALRM) are given by

$$\begin{pmatrix} A \\ Z \\ Z' \end{pmatrix} = \begin{pmatrix} \sqrt{x} & \sqrt{x} & \sqrt{1-2x} \\ \sqrt{1-x} & -x/\sqrt{1-x} & -\sqrt{x(1-2x)/(1-x)} \\ 0 & \sqrt{(1-2x)/(1-x)} & -\sqrt{x/(1-x)} \end{pmatrix} \times \begin{pmatrix} W_L^0 \\ W_R^0 \\ B \end{pmatrix}. \quad (4)$$

Whereas Z couples to the current $J_{3L} - xJ_{\rm em}$ with coupling $e/\sqrt{x(1-x)}$ as in the SM, Z' couples to the current

$$J_{Z'} = xJ_{3L} + (1-x)J_{3R} - xJ_{\rm em} \quad (5)$$

with the coupling $e/\sqrt{x(1-x)(1-2x)}$. The masses of the gauge bosons are given by

$$M_{W_L}^2 = \frac{e^2}{2x}(v_2^2 + v_3^2), \qquad M_Z^2 = \frac{M_{W_L}^2}{1-x}, \qquad M_{W_R}^2 = \frac{e^2}{2x}(v_2^2 + v_4^2 + 2v_6^2), \quad (6)$$

$$M_{Z'}^2 = \frac{e^2(1-x)}{2x(1-2x)}(v_2^2 + v_4^2 + 4v_6^2) - \frac{x^2 M_{W_L}^2}{(1-x)(1-2x)}, \quad (7)$$

where zero $Z - Z'$ mixing has been assumed for simplicity, using the condition [2] $v_2^2/(v_2^2 + v_3^2) = x/(1-x)$. Note that in the ALRM, Δ_R is absent, hence $v_6 = 0$ in the above. Also, the assignment of $(\nu, e)_L$ there is different, hence the Z' of the DLRM is not identical to that of the ALRM. At the LHC, if a new Z' exists which couples to both quarks and leptons, it will be discovered with relative ease. Once $M_{Z'}$ is determined, then the DLRM predicts the existence of $W_R^{\pm}$ with a mass in the range

$$\frac{(1-2x)}{2(1-x)}M_{Z'}^2 + \frac{x}{2(1-x)^2}M_{W_L}^2 < M_{W_R}^2 < \frac{(1-2x)}{(1-x)}M_{Z'}^2 + \frac{x^2}{(1-x)^2}M_{W_L}^2. \quad (8)$$

In the ALRM, since $v_6 = 0$, M_{W_R} takes the value of the upper limit of this range. The prediction of $W_R^{\pm}$ in addition to Z' distinguishes these two models from the multitude of other proposals with an extra $U(1)'$ gauge symmetry.

V. BOUNDS ON $SU(2)_R$

Using Eq. (5) and assuming $\Gamma_{Z'} = 0.05 M_{Z'}$, which is about twice what it would be if Z' decays only into SM fermions, we compute the cross section $\sigma(p\bar{p} \to Z' \to e^+e^-)$ at a center-of-mass energy $E_{\rm cm} = 1.96$ TeV. We show this in Fig. 1 (left) together with the lower bound on $M_{Z'}$ from the Tevatron search, based on an integrated luminosity of $L = 2.5\ {\rm fb}^{-1}$ [7]. We obtain thus $M_{Z'} >$ 850 GeV, and using Eq. (8), $M_{W_R} > 500$ GeV. In Fig. 1 (right) we show the discovery reach of the LHC ($E_{\rm cm} =$ 14 TeV) for observing 10 such events with the cuts $p_T >$ 20 GeV and $|\eta| < 2.4$ for each lepton, and $|m_{e^-e^+} - M_{Z'}| < 3\Gamma_{Z'}$. The dominant SM background from γ/Z (Drell-Yan) is negligible in this case. With an integrated luminosity of $L = 1\ {\rm fb}^{-1}$ ($10\ {\rm fb}^{-1}$), up to $M_{Z'} \sim 1.5$ TeV (2.4 TeV) may be probed.

VI. ODD R PARTICLES

The particles which have odd R are n, h, $W_R^{\pm}$, $\phi_R^{\pm}$, $\Delta_R^{\pm}$, $\phi_1^{\pm}$, ${\rm Re}(\phi_1^0)$, and ${\rm Im}(\phi_1^0)$. Note that ${\rm Re}(\phi_1^0)$ and ${\rm Im}(\phi_1^0)$ are split in mass by the term ${\rm Tr}(\tilde{\Phi}^\dagger \Delta_L \Phi \Delta_R^\dagger)$ as the result of $v_5 \neq 0$. Since m_ν comes from v_5, this splitting is very small and not enough to qualify either to be a dark-matter candidate, because its scattering with nuclei through Z exchange would be much too big for it not to have been detected in direct-search experiments. This leaves the lightest n as a viable dark-matter candidate and we call it a *scotino*. Although it does not couple to Z, it has Z' interactions. To satisfy the Tevatron search limits, $M_{Z'}$ should be greater than 850 GeV. On the other hand, Δ_R has no such constraint and the Yukawa interaction $e_R n_R \Delta_R^+$ may well be the one responsible for the annihilation of n in the early Universe for which the observed relic abundance of dark matter is obtained. Since Δ_R does not couple to quarks, there is also no constraint from DM direct-search experiments for these interactions. Note that the Yukawa interactions $\bar{\nu}_L n_R \phi_1^0$ and $\bar{e}_L n_R \phi_1^-$ also exist, but are too small because they are proportional to m_e.

A simple variation of this model also allows neutrino masses to be radiatively generated by dark matter, i.e. *scotogenic* [8]. Instead of Δ_L, we add a scalar singlet $\chi \sim (1, 1, 1, 0; -1)$, then the trilinear scalar term ${\rm Tr}(\Phi\tilde{\Phi}^\dagger)\chi$ is allowed. Using the soft term χ^2 to break L to $(-)^L$, a scotogenic neutrino mass is obtained as shown in Fig. 2.

VII. DARK MATTER

The lightest n can be a stable weakly interacting neutral particle. It is thus a good candidate for the dark matter of the Universe. We assume that Δ_R^+ is much lighter than W_R^+ and Z'; hence the dominant annihilation of n is given by $nn \to e_R^- e_R^+$ through the exchange of Δ_R^+ with Yukawa coupling f_n. Using the approximation $\langle\sigma v\rangle \simeq a + bv^2$

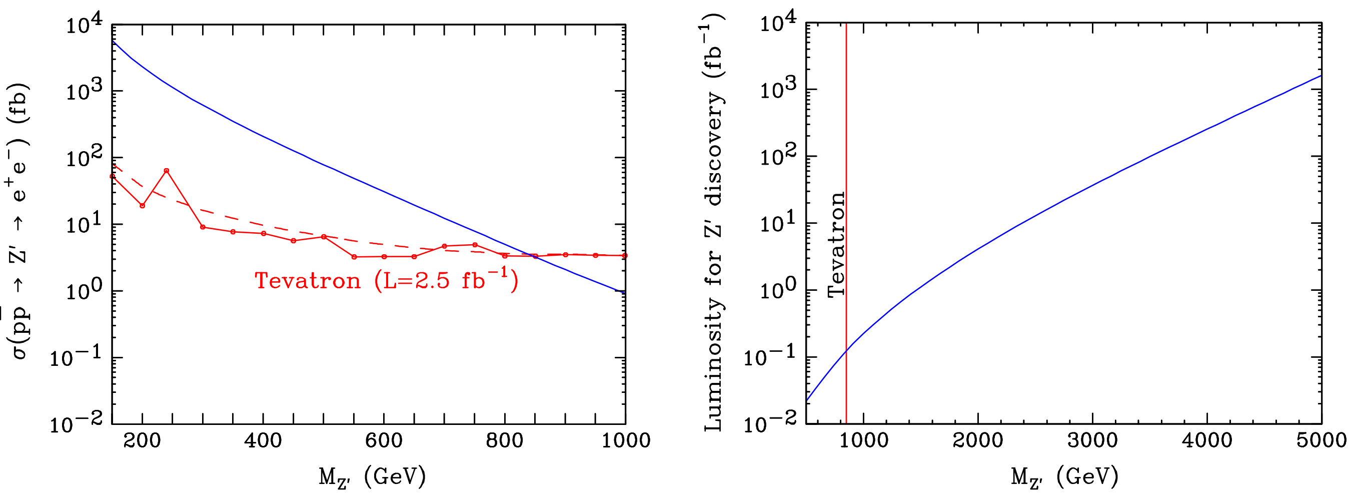

FIG. 1 (color online). (left) Lower bound on $M_{Z'}$ of the DLRM from the Tevatron dielectron search. (right) Luminosity for Z' discovery by 10 dielectron events at the LHC.

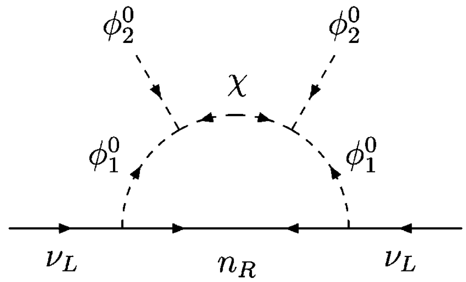

FIG. 2. One-loop scotogenic neutrino mass.

for the thermally averaged annihilation cross section of n multiplied by its velocity, we find

$$a = 0, \qquad b = \frac{f_n^4}{48\pi m_n^2} r^2(1 - 2r + 2r^2), \tag{9}$$

where $r = (1 + w^2)^{-1}$ with $w = m_{\Delta_R^+}/m_n$. Under the usual assumption that n decoupled from the SM particles in the early Universe when it became nonrelativistic, its relic density is given by

$$\Omega_n h^2 = \frac{8.76 \times 10^{-11}\ \mathrm{GeV}^{-2}}{g_{*(T_F)}^{1/2}(a/x_F + 3b/x_F^2)}, \qquad x_F = \ln\frac{0.0955 M_P m_n (a + 6b/x_F)}{\sqrt{g_* x_F}}, \tag{10}$$

where T_F is the freeze-out temperature, $x_F = m_n/T_F$, M_P the Planck mass, and g_* the number of relativistic degrees of freedom at T_F. In Fig. 3, we present the values of the relic abundance $\Omega_n h^2$ as a function of m_n for the cases $w = m_{\Delta_R^+}/m_n = 1.1$, 2, and 5, with $f_n = 1$. The measured values of Ωh^2 for cold dark matter by the Wilkinson Microwave Anisotropy Probe (WMAP) [9] are obtained for a wide range of n and Δ_R^+ mass values.

Since n always interacts with a lepton in this model, its annihilation in the Earth's vicinity will produce high-energy electrons and positrons, which may be an explanation of such recently observed events in the PAMELA [10] and ATIC [11] experiments.

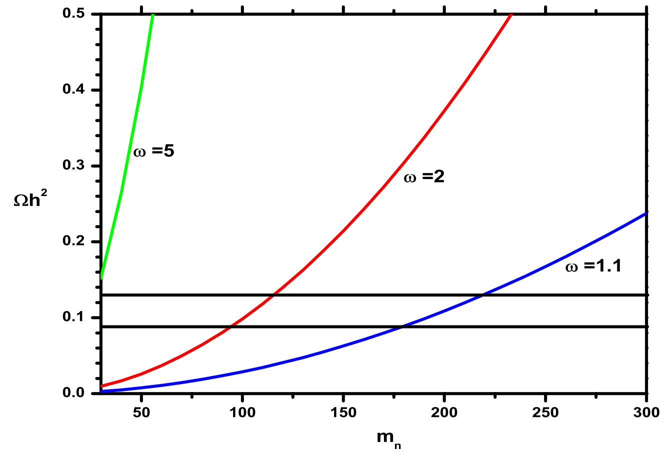

FIG. 3 (color online). Relic density of n as a function of its mass and $w = m_{\Delta_R^+}/m_n$. Horizontal lines correspond to the experimental limits at 1σ.

VIII. CONCLUSION

We have proposed in this paper the notion that neutrinos and dark-matter fermions (scotinos) exist in parallel as members of doublets under $SU(2)_L$ and $SU(2)_R$ respectively. As such, both interact with leptons: neutrinos through W_L and scotinos through W_R. The resulting model (DLRM) allows for the definition of a generalized lepton number and thus R parity in a nonsupersymmetric context, and has a host of verifiable predictions at the TeV scale.

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