Dark Left-Right Model: CDMS, LHC, etc.

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Abstract. The Standard Model of particle interactions is extended to include fermion doublets \( (n,e)_R \) transforming under the gauge group \( SU(2)_R \) such that \( n \) is a Dirac scotino (dark-matter fermion), with odd \( R \) parity. Based on recent CDMS data, it is shown how this new dark left-right model (DLRM2) favors a \( Z^\prime \) gauge boson at around 1 or 2 TeV and be observable at the LHC. The new \( W^\pm_R \) gauge bosons may also contribute significantly to lepton-flavor-changing processes such as \( \mu \rightarrow e\gamma \) and \( \mu - e \) conversion in a nucleus or muonic atom.

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LEFT-RIGHT EXTENSION OF STANDARD MODEL

If the Standard Model (SM) of particle interactions is extended to accommodate \( SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \), then the conventional assignment of

\[
\begin{align*}
(v,l)_L & \sim (1,2,1,-1/2), \\
(u,d)_L & \sim (3,2,1,1/6), \\
(v,l)_R & \sim (1,1,2,-1/2), \\
(u,d)_R & \sim (3,1,2,1/6),
\end{align*}
\]

implies the well-known result that \( X = (B-L)/2 \) and \( Y = T^R_3 + (B-L)/2 \). There must then be Higgs bidoublets

\[
\Phi = \left( \begin{array}{c} \phi^0_1 \\ \phi^-_1 \\ \phi^0_2 \\ \phi^+_2 \end{array} \right), \quad \bar{\Phi} = \left( \begin{array}{c} \bar{\phi}^0_1 \\ -\bar{\phi}^-_1 \\ \bar{\phi}^0_2 \\ -\bar{\phi}^+_2 \end{array} \right),
\]

both transforming as \( (1,2,2,0) \), yielding lepton Dirac mass terms

\[
\begin{align*}
m_l &= f_i \langle \phi^0_2 \rangle + f'_i \langle \bar{\phi}^0_2 \rangle, \\
m_\nu &= f_i \langle \phi^0_1 \rangle + f'_i \langle \bar{\phi}^0_2 \rangle,
\end{align*}
\]

and similarly in the quark sector. This results in the appearance of phenomenologically undesirable tree-level flavor-changing neutral currents from Higgs exchange, as well as inevitable \( W_L - W_R \) mixing. If supersymmetry is imposed, then \( \Phi \) can be eliminated, but then \( (M_\nu)_{ij} \propto (M_\ell)_{ij} \) as well as \( (M_d)_{ij} \propto (M_u)_{ij} \), contrary to what is observed. Hence the prevalent thinking is that \( SU(2)_R \times U(1)_{B-L} \) is actually broken down to \( U(1)_Y \) at a very high scale from an \( SU(2)_R \) Higgs triplet \( (\Delta^+_R, \Delta^+_R, \Delta^0_R) \sim (1,1,3,1) \) which provides \( \nu_R \) at the same time with a large Majorana mass from \( \langle \Delta^0_R \rangle \).

The canonical seesaw mechanism for neutrino mass is thus implemented and everyone should be happy. But wait, no remnant of the \( SU(2)_R \) gauge symmetry is detectable at the TeV scale and we will not know if \( \nu_R \) really exists. Is there a natural way to lower the \( SU(2)_R \times U(1)_{B-L} \) breaking scale?
The answer was already provided 23 years ago [1] in the context of the superstring-inspired supersymmetric $E_6$ model. The fundamental $27$ fermion representation here is decomposed under $[(SO(10), SU(5))]$ as

$$27 = (16, 10) + (16, 5^*) + (16, 1) + (10, 5) + (10, 5^*) + (1, 1).$$ (5)

Under its maximum subgroup $SU(3)_C \times SU(3)_L \times SU(3)_R$, the $27$ is organized instead as $(3, 3^*, 1) + (1, 3, 3^*) + (3^*, 1, 3)$, i.e.

$$\begin{pmatrix}
    d & u & h \\
    d & u & h \\
    d & u & h
\end{pmatrix}
+ \begin{pmatrix}
    N & E^c & \nu \\
    E & N^c & e \\
    \nu^c & e^c & n^c
\end{pmatrix}
+ \begin{pmatrix}
    d^c & d^c & d^c \\
    u^c & u^c & u^c \\
    h^c & h^c & h^c
\end{pmatrix}.$$ (6)

It was realized [1] in 1987 that there are actually two left-right options: (A) Let $E_6$ break down to the fermion content of the conventional $SO(10)$, given by $(16, 10) + (16, 5^*) + (16, 1)$, which is the usual left-right model which everybody knows. (B) Let $E_6$ break down to the fermion content given by $(16, 10) + (10, 5^*) + (1, 1)$ instead, thereby switching the first and third rows of $(3^*, 1, 3)$ and the first and third columns of $(1, 3, 3^*)$. Thus $(\nu, e)_R$ becomes $(n, e)_R$ and $n_R$ is not the mass partner of $\nu_L$. This is referred to by the Particle Data Group as the Alternative Left-Right Model (ALRM). Here the usual left-handed lepton doublet is part of a bidoublet:

$$\begin{pmatrix}
    \nu \\
    e
\end{pmatrix}_L \sim (1, 2, 2, 0).$$ (7)

In this supersymmetric model, $\psi_L$ is still the Dirac mass partner of $\psi_R$ and gets a seesaw mass, whereas $n_R$ (which couples to $e_R$ through $W_R$) mixes with the usual neutralinos, the lightest of which is a dark-matter candidate.

## DARK LEFT-RIGHT MODEL

Two simpler nonsupersymmetric versions of the ALRM with $n_R$ as dark matter have recently been proposed [3, 4]. We call them Dark Left-Right Models (DLRM and DLRM2). We impose a global $U(1)$ symmetry $S$, so that under $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$, a generalized lepton number is conserved, such that $L = S - T_{3R}$ in DLRM and $L = S + T_{3R}$ in DLRM2. The resulting dark-matter fermion $n_R$ has $L = 0$ (Majorana) in DLRM and $L = 2$ (Dirac) in DLRM2. This talk is on DLRM2, with particle content [4] under $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$ given below:

$$\psi_L = (\nu, e)_L \sim (1, 2, 1, -1/2; 1), \quad \psi_R \sim (1, 1, 1, 0; 1),$$ (8)

$$\psi_R = (n, e)_R \sim (1, 1, 2, -1/2; 3/2), \quad n_L \sim (1, 1, 1, 0; 2),$$ (9)

$$Q_L = (u, d)_L \sim (3, 2, 1, 1/6; 0), \quad d_R \sim (3, 1, 1, -1/3; 0),$$ (10)

$$Q_R = (u, h)_R \sim (3, 1, 2, 1/6; -1/2), \quad h_L \sim (3, 1, 1, -1/3; -1),$$ (11)

$$\Phi \sim (1, 2, 2, 0; -1/2), \quad \Phi^e \sim (1, 2, 2, 0; 1/2),$$ (12)

$$\Phi_L = (\phi^0_L, \phi^+_L) \sim (1, 2, 1, 1/2; 0), \quad \Phi_R = (\phi^0_R, \phi^+_R) \sim (1, 1, 2, 1/2; 1/2).$$ (13)
As a result, the Yukawa terms $\bar{\psi}_L \Phi \psi_R$, $\bar{\psi}_L \tilde{\Phi} L \nu_R$, $\bar{Q}_L \Phi Q_R$, $\bar{Q}_R \Phi h_L$ are allowed, whereas $\bar{\psi}_L \Phi \psi_R$, $\bar{Q}_L \Phi Q_R$ are forbidden together with the bilinear terms $\bar{n}_L \nu_R$, $\bar{h}_L d_R$. The breaking of $SU(2)_L \times U(1)_Y$ leaves $L = S + T_3R$ unbroken, so that $v_2 = \langle \phi^0 \rangle \neq 0$ (if $\phi^0$ has $L = 0$), but $\langle \phi^0 \rangle = 0$ (if $\phi^0$ has $L = -1$). The former contributes to $m_e$ and $m_u$, whereas the latter means that $v_L$ and $n_R$ are not Dirac mass partners and can be completely different particles. In fact, $m_\nu$, $m_d$ come from $v_3 = \langle \phi^0_L \rangle$, and $m_n$, $m_h$ from $v_4 = \langle \phi^0_R \rangle$. This structure guarantees the absence of tree-level flavor-changing neutral currents. As for the gauge bosons and their interactions, let $e/g_L = \sin \theta_W$, $e/g_R = 
abla$, $e/g_X = \sqrt{1 - s^2_L - s^2_R}$, then

$$A = s_L W_L^0 + s_R W_R^0 + \sqrt{c^2_L - s^2_R} X,$$

$$Z = c_L W_L^0 - (s_L s_R/c_L) W_R - (s_L \sqrt{c^2_L - s^2_R}/c_L) X,$$

$$Z' = (\sqrt{c^2_L - s^2_R}/c_L) W_R - (s_R/c_L) X,$$

$$g_Z = e/s_L c_L, \quad J_Z = J_{3L} - s^2_L J_{em},$$

$$g_{Z'} = e/s_R c_L \sqrt{c^2_L - s^2_R}, \quad J_{Z'} = s^2_R J_{3L} + c^2_L J_{3R} - s^2_R J_{em}. \quad (18)$$

To avoid $Z - Z'$ mixing at tree level, the condition $v_2^2/(v_2^2 + v_3^2) = s^2_R/c^2_L$ must be imposed. In that case, $M_{W_L} \sim \sqrt{c^2_L - s^2_R}/c_L M_{Z'}$. Note that $W_R$ does not mix with $W_L$ because they have different $R$ parity. In Fig. 1, the present Tevatron bound on $M_{Z'}$ is shown for various values of $s^2_R$, showing a typical bound of about 1 TeV.
CDMS AND MORE

The usual leptons have $L = 1$ as expected, but there are now new particles also with lepton number: $W^+_R$, $\phi^+_R$, $\psi^+_R$ have $L = 1$ and $h$ has $L = -1$ as well as $B = 1/3$. Thus they all have odd $R$ parity, i.e. $R = (-)^{3B+L+2j} = -1$, even though the model is nonsupersymmetric. The scotino $n$ has $L = 2$ and thus also odd $R$. The lightest $n$ is a dark-matter candidate, and will be considered below in the context of recent data from the CDMS-II collaboration [5]. Two possible dark-matter signal events were observed with an expected background of $0.9 \pm 0.1$. The most stringent bound on the elastic spin-independent scattering cross section of $nq \rightarrow nq$ occurs at $m_n = 70$ GeV, and it is $3.8 \times 10^{-8}$ pb. In the DLRM2,

$$\mathcal{L} = \frac{g^2_{ZnV}}{M^2_{Z^{'}}}(\bar{n}\gamma_\mu n)(u\gamma^\mu u + d\gamma^\mu d),$$

where $nV = c^2_L/4$, $uV = c^2_L/4 - 5s^2_R/12$, $dV = s^2_R/12$. Let $f_P = g^2_{ZnV}(2uV + dV)/M^2_{Z^{'}}$, $f_N = g^2_{ZnV}(uV + 2dV)/M^2_{Z^{'}}$, then

$$\sigma_0 \approx \frac{4m^2_P[Zf_P + (A - Z)f_N]^2}{\pi A}.$$  

Using $^{73}$Ge, i.e. $Z = 32$ and $A - Z = 41$, as an estimate, the CDMS bound (of $3.8 \times 10^{-8}$ pb at $m_n = 70$ GeV) implies a bound on $M_{Z^{'}}$. In Fig. 2, the resulting lower bounds on $M_{Z^{'}}$ from the Tevatron search and from CDMS are plotted as functions of $s^2_R$.

**FIGURE 2.** Lower bounds on $M_{Z^{'}}$ vs $s^2_R$ from the Tevatron search (red solid line) and from the CDMS search at $m_n = 70$ GeV (blue dashed line). The dotted segments assume a simple extrapolation of the Tevatron data.
To obtain the correct dark-matter relic abundance, the annihilation of $\bar{n}n \to Z' \to SM$ fermions is considered. The thermally averaged cross section multiplied by the relative velocity of the annihilating particles is given by

$$\langle \sigma v_{\text{rel}} \rangle_{Z'} = \frac{\pi \alpha^2 (3 - 9 r + 10 r^2) m_n^2}{2 c^4_L r^2 (1 - r)^2 (4 m_n^2 - M_{Z'}^2)^2},$$

where $r = s_R^2/c_L^2$. Fixing the above at 1 pb, the values of $m_n$ and $M_{Z'}$ are constrained as a function of $s_R^2$. For $m_n = 70$ GeV, there is no solution, but if $m_n$ is greater than about 300 GeV, solutions exist which are consistent with the Tevatron bound as well as the CDMS bound. In the range $0.3 < m_n < 1.0$ TeV, the latter is well approximated by $\sigma_0 < 2.2 \times 10^{-7}$ pb ($m_n/1$ TeV)$^{0.86}$. In Fig. 3, the cases $m_n = 400$ and 600 GeV are shown.

The $\bar{n}n$ annihilation to leptons through $W_R^\pm$ exchange also contributes, i.e.

$$\langle \sigma v_{\text{rel}} \rangle_{W_R} = \frac{3 g_R^4 m_n^2}{64 \pi (m_n^2 + M_{W_R}^2)^2},$$

but it is subdominant and has been neglected.

**LHC AND MORE**

At the LHC ($E_{cm} = 14$ GeV), $Z'$ may be discovered with 10 dilepton events. Using the cuts

- $p_T > 20$ GeV for each lepton,
- $|\eta| < 2.4$ for each lepton,
- $|M_{l^- l^+} - M_{Z'}| < 3 \Gamma_{Z'}$,

the SM background is negligible. With an integrated luminosity of 1 fb$^{-1}$, the discovery reach of the $Z'$ of the DLRM2 is about 2 TeV, as shown in Fig. 4.
To distinguish this $Z'$ from others, the following ratios [6] may be considered:

\[
\frac{\Gamma(Z' \to t\bar{t})}{\Gamma(Z' \to \mu^-\mu^+)} = \frac{(9 - 24r + 17r^2)}{3(1 - 4r + 5r^2)} = 4.44 \ (g_L = g_R),
\]

\[
\frac{\Gamma(Z' \to b\bar{b})}{\Gamma(Z' \to \mu^-\mu^+)} = \frac{5r^2}{3(1 - 4r + 5r^2)} = 0.60 \ (g_L = g_R),
\]

where $r = s_R^2/c_L^2$. In the conventional left-right model, the numerator for $b\bar{b}$ is changed to $(9 - 12r + 8r^2)$, i.e. 13.6 larger ($g_L = g_R$). In the ALRM, the denominator for both is changed to $3(2 - 6r + 5r^2)$, i.e. 2.6 larger ($g_L = g_R$).

There are also important loop effects [2] on rare processes from the new interactions $\gamma W_R^+W_R^-$, $ZW_R^+W_R^-$, $W_R^+\bar{n}_R e_R$, $W_R^+\bar{u}_R h_R$, etc. The anomalous magnetic moment of the muon receives a contribution of order $10^{-10}$, below the present experimental sensitivity of $10^{-9}$. The flavor-changing radiative decay $\mu \to e\gamma$ has the branching fraction

\[
B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left(\frac{s_L M_{W_L}}{s_R M_{W_R}}\right)^4 \left|\sum_i U_{\mu i} U_{ei} F_\gamma(r_i)\right|^2,
\]

where $r_i = n_{ri}^2/M_{W_R}^2$ and

\[
F_\gamma(r_i) = \frac{r_i(-1 + 5r_i + 2r_i^2)}{(1 - r_i)^3} + \frac{6r_i^3 \ln r_i}{(1 - r_i)^4}.
\]
It is suppressed by $M_{W_R}$ and for $M_{W_R} = 1.17$ TeV (corresponding to $M_{Z'} = 1.4$ TeV), the current experimental bound of $1.2 \times 10^{-11}$ implies $|\sum_i U_{\mu i} U_{e i} F_Z(r_i)| < 0.05$ for $g_L = g_R$. A more sensitive probe of the existence of these new interactions is $\mu \rightarrow eee$ or $\mu - e$ conversion in a nucleus or muonic atom [7]. The reason is that there is an effective $\mu \rightarrow eZ$ vertex from $ZW^+_R W^-_R$ and $W^+_R \bar{n}_R e_R$, given by

$$g_{\mu e Z} = \frac{e^3 s_L}{16 \pi^2 s_R c_L} \sum_i U_{\mu i} U_{e i} F_Z(r_i),$$

(27)

where $F_Z(r_i) = r_i / (1 - r_i) + r_i^2 \ln r_i / (1 - r_i)^2$, which is not suppressed if $r_i$ is not small, which holds even if the $SU(2)_R$ scale is much greater than the electroweak scale. This unusual (nondecoupling) property depends crucially on the $ZW^+_R W^-_R$ vertex, which is not available in other extensions of the SM, including all $U(1)'$ models. The current experimental bound of $1.0 \times 10^{-12}$ on $B(\mu \rightarrow eee)$ implies $|\sum_i U_{\mu i} U_{e i} F_Z(r_i)| < 1.44 \times 10^{-3}$ for $g_L = g_R$.

**CONCLUSION**

The presence of $\nu_R$ is unavoidable in a left-right gauge extension of the Standard Model. However, it does not have to be the Dirac mass partner of $\nu_L$. In that case, it should be renamed $n_R$ and could function as a scotino, i.e. a dark-matter fermion. In the context of the recently proposed new dark left-right model (DLRM2), latest CDMS observations are shown to be consistent with the lightest $n$ at about a few hundred GeV in mass with the new $Z'$ gauge boson at less than 2 TeV. The latter should then be accessible directly at the LHC, while the $W^\pm_R$ gauge boson may contribute indirectly to enhancing rare lepton-flavor-changing processes such as $\mu \rightarrow eee$ and $\mu - e$ conversion in a nucleus or muonic atom.

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