Dark-matter fermion from left-right symmetry

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Matter-Dark-Matter Correspondence in Left-Right Symmetry

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Abstract

In an unconventional realization of left-right symmetry, the particle corresponding to the left-handed neutrino ν_L (with $SU(2)_L$ interactions) in the right-handed sector, call it n_R (with $SU(2)_R$ interactions), is not its Dirac mass partner, but a different particle which may be a dark-matter candidate. In parallel to leptogenesis in the $SU(2)_L$ sector, asymmetric production of n_R may occur in the $SU(2)_R$ sector. This mechanism is especially suited for n_R mass of order 1 to 10 keV, i.e. warm dark matter, which is a possible new paradigm for explaining the structure of the Universe at all scales.

In our present Universe, there is quite a bit of matter, but not much antimatter, i.e. we have a matter-antimatter asymmetry, usually called the baryon asymmetry. There is also a lot of dark matter, but its nature is unknown. It is possible that dark matter is related to ordinary matter in that it comes partly also from matter carrying baryon number so that there is also dark antimatter. In that case, the mechanism which generates the dark matter of the Universe may well be the parallel of that which generates the baryon asymmetry.

It is now a fact of particle physics that neutrinos have mass. There are many theoretical mechanisms [1] for this to happen, but the first and simplest idea remains that of the canonical seesaw [2], where a heavy singlet fermion, often referred to as a right-handed neutrino, is added to the standard model for each family of leptons. This implies the extra terms given by

$$\mathcal{L}_\nu = -f(\bar{\nu}_L \phi^0 - \bar{e}_L \phi^+)\nu_R - \frac{1}{2} M \nu_R^T \nu_R + H.c., \tag{1}$$

which result in a Majorana neutrino mass $m_\nu \simeq -m_D^2/M$, where $m_D = f\langle\phi^0\rangle = fv$. This very famous simple formula also shows that if M is large, m_ν is small because the Dirac mass m_D comes from electroweak symmetry breaking, i.e. $v = 174$ GeV, as do all quark and charged lepton masses. A large M also has a second very important consequence. It allows the decay of ν_R to $e^\pm \phi^\mp$, which may then create a lepton asymmetry in the early Universe [3], and gets converted into the present observed baryon (matter-antimatter) asymmetry during the $SU(2)_L$ phase transition [4].

Consider now the conceptually attractive idea of a left-right extension of the standard model. The existence of ν_R becomes mandatory and it appears as part of the $SU(2)_R$ doublet, i.e. $(\nu, e)_R$. If $SU(2)_R$ is broken at a high scale by a Higgs triplet $(\Delta^{++}, \Delta^+, \Delta^0)$, then again ν_R acquires a large Majorana mass proportional to $\langle\Delta^0\rangle$. The seesaw mechanism works as before but it is very difficult to distinguish this left-right extension experimentally from the standard model at energies far below M.

Besides neutrino mass and matter-antimatter asymmetry, the nature and origin of dark matter are two equally important issues. Whereas there are myriads of theoretical proposals for what dark matter is, recent astrophysical observations regarding the structure of the Universe at all scales are lending increasing credence [5] to the notion that it is warm and suitably explained by a sterile neutrino [6] with mass in the range 1 to 13 keV. In this paper, it is proposed that ν_R in a suitably extended left-right model may in fact behave as a sterile neutrino which is absolutely stable in its own right. This notion is fundamentally different from the usual concept of a sterile neutrino which mixes with the active neutrinos. That would make the sterile neutrino unstable and not suitable as a dark-matter candidate unless the mixing is very tiny. This mixing also exists in a recent left-right extension [7] where the lightest ν_R has a Majorana mass of order keV.

The origin of the idea that ν_R does not mix with ν_L started with superstring-inspired E_6 models. It was realized that with the particle content of the fundamental $\underline{27}$ representation, an alternative left-right model is possible [8]. More recently, its relevance to dark matter in two simple nonsupersymmetric versions [9, 10] was discussed. In both cases, the $SU(2)_R$ doublet is $(n, e)_R$ where n_R is not the Dirac mass partner of ν_L. It has been termed a "scotino", i.e. a dark fermion. In the first model [9], n_R is a Majorana particle of perhaps 150 GeV. In the second model [10], it is a Dirac particle of perhaps 500 GeV. In this paper, a third simple variation is offered such that n_R is a Majorana particle of 1 to 10 keV. As such, it will be shown that a $\nu_L - n_R$ correspondence exists in left-right symmetry in all their fundamental interactions. The apparent difference, i.e. ν_L is "active" and n_R is "sterile", only comes from the fact that the $SU(2)_R$ breaking scale is much higher than that of $SU(2)_L$.

Let the gauge symmetry $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ be supplemented by a global U(1) symmetry S'. The fermion and scalar particle content of this model is listed in Table. 1. The purpose of the imposed S' symmetry is to distinguish the scalar bidoublet η

particles	$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$(B-L)/2$	S'
$(u,d)_L$	3	2	1	1/6	0
$(u,h)_R$	3	1	2	1/6	–1/2
d_R	3	1	1	–1/3	0
h_L	3	1	1	–1/3	–1
$(\nu,e)_L$	1	2	1	–1/2	0
$(n,e)_R$	1	1	2	–1/2	1/2
ν_R	1	1	1	0	0
n_L	1	1	1	0	1
(ϕ_L^+,ϕ_L^0)	1	2	1	1/2	0
(ϕ_R^+,ϕ_R^0)	1	1	2	1/2	1/2
η	1	2	2	0	–1/2

Table 1: Particle content of the fermions and scalars of this unconventional left-right model.

from its dual $\tilde{\eta} = \sigma_2 \eta^* \sigma_2$ which transforms in the same way as η under $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Specifically,

$$\eta = \begin{pmatrix} \eta_1^0 & \eta_2^+ \\ \eta_1^- & \eta_2^0 \end{pmatrix}, \quad \tilde{\eta} = \begin{pmatrix} \bar{\eta}_2^0 & -\eta_1^+ \\ -\eta_2^- & \bar{\eta}_1^0 \end{pmatrix}. \tag{2}$$

As a result, η_2^0 coulples to $\bar{e}_L e_R$, $\bar{\eta}_2^0$ coulples to $\bar{u}_L u_R$, η_1^0 coulples to $\bar{\nu}_L n_R$, $\bar{\eta}_1^0$ coulples to $\bar{d}_L h_R$, ϕ_L^0 couples to $\bar{d}_L d_R$, and ϕ_R^0 couples sto $\bar{h}_R h_L$. As ϕ_R^0 acquires a large vacuum expectation value, $SU(2)_R \times U(1)_{B-L}$ is broken to $U(1)_Y$ and S' is also broken, but the combination $S = S' + T_{3R}$ remains unbroken. To break $SU(2)_L \times U(1)_Y$ to $U(1)_Q$, the scalar fields ϕ_L^0 and η_2^0 (both having $S=0$) acquire vacuum expectation values but not η_1^0 which has $S=-1$. This means that n_R (which has $S=1$) is not the Dirac mass partner of ν_L.

It is easy to see that all the standard-model particles have $S=0$. Some of the new particles also have $S=0$, i.e. Z', η_2^+, η_2^0, ϕ_R^0, whereas the others have $S=1$, i.e. n, $\bar{h}$, W_R^+, ϕ_R^+, η_1^+, $\bar{\eta}_1^0$. As for baryon number and lepton number, u,d,h all have $B=1/3$, and ν,e,n all have $L=1$. Note that ν gets a Dirac mass from ϕ_L^0 and n gets a Dirac mass from ϕ_R^0. Using the canonical seesaw mechanism, the singlets ν_R $(L=1, S=0)$ and n_L $(L=1, S=1)$

are assumed to have large Majorana masses which break L softly to $(-1)^L$ and S softly to $(-1)^S$. Thus both ν_L and n_R obtain seesaw masses. Naively, if the $SU(2)_R$ breaking scale is $10^{2.5}$ that of $SU(2)_L$, then $m_n \sim 10^5\ m_\nu \sim 10$ keV if $m_\nu \sim 0.1$ eV. The corresponding Fermi constant for n is then $10^{-5}\ G_F$, which makes it effectively sterile. The lightest scotino n is absolutely stable (having odd S) in complete analogy to the lightest ν which is also absolutely stable. Note that $n_i \to n_j \gamma$ is possible just as $\nu_i \to \nu_j \gamma$ is possible, but these lifetimes are much greater than that of the Universe. Consequently, it is possible that the three scotinos permeate the Universe as warm dark matter (with presumably $\Omega_n h^2 \sim 0.1$), and the three neutrinos as hot dark matter (with a much smaller relic density $\Omega_\nu h^2 \sim 0.001$ if $\sum m_\nu \sim 0.1$ eV).

The decays of the heavy ν_R to $\nu\phi_L^0 - e^-\phi_L^+$ and $\bar{\nu}\bar{\phi}_L^0 - e^+\phi_L^-$ and heavy n_L to $n\phi_R^0 - e^-\phi_R^+$ and $\bar{n}\bar{\phi}_R^0 - e^+\phi_R^-$ both create lepton asymmetries which get converted to a $B-L$ asymmetry through the $SU(2)_L$ and $SU(2)_R$ sphalerons. Matter and dark matter both have $B-L$. They are distinguished only by S. Once past the electroweak phase transition, n becomes effectively a sterile neutrino. For $m_\nu \sim 0.1$ eV, its relic density is about $\Omega_\nu h^2 = 0.001$. To obtain the observed dark-matter value $\Omega_n h^2 = 0.1$ for $m_n \sim 10$ keV, its number density should be about 10^{-3} that of neutrinos. It is interesting to note that if $SU(2)_L$ breaks at a much higher scale than $SU(2)_R$, then the scotinos may become the neutrinos and vice versa, and the Universe would look very much the same, except for a left-right switch.

There are two lepton asymmetries in the early Universe, one each from ν_R and n_L decay. Their exact values depend on various parameters such as the CP violation in the 3×3 Yukawa coupling matrices in the $SU(2)_L$ and $SU(2)_R$ sectors respectively. As the Universe cools below the $SU(2)_R$ and $SU(2)_L$ phase transitions, these two asymmetries are converted into two $B-L$ asymmetries, one for the $S=0$ fermions, i.e. the usual quarks and leptons, and the other for the $S=1$ fermions, i.e. the h quarks and the n scotinos. However, unlike the usual quarks, the h quarks all decay away, i.e. $h \to ue\bar{n}$, hence only the n scotinos remain. If their present number density is about 10^{-3} that of the neutrinos, which is presumably a realizable scenario, if for example [7] a late decaying particle exists which releases enough entropy after the scotino freeze-out at a temperature of order 1 GeV, then $m_n \sim 10$ keV works very well for understanding the structure of the Universe at all scales [5]. It is especially natural for explaining the deficit of dwarf spheroidal galaxies relative to the cold-dark-matter scenario. The role of a late decaying particle may be a heavy scotino with a mass of order 1 GeV, as suggested in Ref. [7]. In that case, only two n scotinos are light. An alternative scenario is to have a light scalar singlet which couples to $\Phi^\dagger\Phi$ as in many proposed extensions of the standard model invoking the idea of a Higgs portal. The decay of this scalar to photons in one loop may also increase the entropy of the Universe by a large factor before big bang nucleosynthesis.

As a very weakly interacting particle of 10 keV, n_R is not observable at underground experiments searching for dark matter through nuclear recoil. Since it does not mix with ν_L, it is also not a product of beta decay. It is in fact absolutely stable, so it cannot be directly observed astrophysically through radiative decay as is the case with the usual sterile neutrino, thus evading the upper bound of about 2 keV from galactic X-ray observations. On the other hand, the lower bound of a few keV still holds from Lyman-α forest observations. As for the one-loop annihilation of $nn \to \gamma\gamma$, its cross section is further suppressed by the $SU(2)_R$ breaking scale. This again makes it very difficult to observe. At the Large Hadron Collider (LHC), it may show up if there is a light enough h quark, say of order 1 TeV. Such quarks are easily produced in pairs by gluons. Once produced, they decay to n and $\bar{n}$, i.e.

$$h \to u\bar{n}e^-, \qquad \bar{h} \to \bar{u}ne^+, \tag{3}$$

through $W_R^\pm$ exchange. Thus h looks like a fourth-generation d quark, which has the current bound of $M > 495$ GeV [11]. There is, however, a very important difference which should be explored in future LHC analyses. Whereas a fourth-generation d has suppressed branching fractions into leptons, the lightest h decays only semileptonically. This makes it much easier to discover if its production is kinematically allowed. Another possible production mechanism is gluon $+\ u \to hW_R^+$.

This model also predicts two effective Higgs doublets [12], i.e. (ϕ_L^+, ϕ_L^0) and (η_2^+, η_2^0). However, unlike the canonical case, such as that of the Minimal Supersymmetric Standard Model (MSSM), where the u quarks couple to one doublet with $m_u \sin^{-1}\beta$, and the d quarks and charged leptons couple to the other doublet with $m_d \cos^{-1}\beta$ and $m_e \cos^{-1}\beta$, the charged leptons now team up instead with the u quarks with coupling $m_e \sin^{-1}\beta$. This means that $H^+ \to \tau^+\nu_\tau$ is suppressed by $\cot^4\beta$ relative to the prediction of the MSSM. For large $\tan\beta$, this channel would be unobservable and may serve to discriminate this two-Higgs-doublet structue against that of the MSSM.

Let $e/g_L = s_L = \sin\theta_W$ and $s_R = e/g_R$ with $c_{L,R} = \sqrt{1 - s_{L.R}^2}$, then $g_B = e/\sqrt{c_L^2 - s_R^2}$ and the neutral gauge bosons of this model are given by

$$\begin{pmatrix} A \\ Z \\ Z' \end{pmatrix} = \begin{pmatrix} s_L & s_R & \sqrt{c_L^2 - s_R^2} \\ c_L & -s_L s_R/c_L & -s_L\sqrt{c_L^2 - s_R^2}/c_L \\ 0 & \sqrt{c_L^2 - s_R^2}/c_L & -s_R/c_L \end{pmatrix} \begin{pmatrix} W_L^0 \\ W_R^0 \\ B \end{pmatrix}. \tag{4}$$

Whereas Z couples to the current $J_Z = J_{3L} - s_L^2 J_{\rm em}$ with coupling $e/s_L c_L$ as in the standard model, Z' couples to the current $J_{Z'} = s_R^2 J_{3L} + c_L^2 J_{3R} - s_R^2 J_{\rm em}$ with coupling $g_{Z'} = e/s_R c_L \sqrt{c_L^2 - s_R^2}$. Although $Z - Z'$ mixing exists, it is negligible because it is of order $M_Z^2/M_{Z'}^2$ which is assumed to be $\sim 10^{-5}$. However, since Z has a component of W_R^0, it also couples to $W_R^+ W_R^-$. This appears to induce an effective one-loop flavor-changing coupling such as $\bar{e}\gamma^\alpha \mu Z_\alpha$ through n exchange or $\bar{u}\gamma^\alpha c Z_\alpha$ through h exchange. A naive calculation of the integral involved seems to indicate that this effect is not suppressed if m_h is comparable to M_{W_R}, which would be a curious example of non-decoupling. A full calculation taking into account the contributions of the would-be Goldstone modes of the spontaneous symmetry breaking of $SU(2)_R$ shows that this effective coulping is in fact zero in the limit $SU(2)_L$ is not broken.

If soft breaking of S' is allowed through the terms $\bar{n}_L \nu_R$, $\bar{h}_L d_R$, $det(\eta)$, and $\Phi_L^\dagger \tilde{\eta} \Phi_R$, then n mixes with ν (and h with d), so the usual sterile-neutrino scenario is recovered, but with the addition of the exotic h quarks.

In conclusion, a new left-right extension of the standard model has been proposed. The neutral fermion in the $SU(2)_R$ doublet $(n,e)_R$ is not the Dirac mass partner of the neutrino in the $SU(2)_L$ doublet $(\nu,e)_L$. It is in fact a scotino, i.e. an absoultely stable dark-matter fermion. Both ν_L and n_R obtain seesaw masses from the corresponding singlets ν_R and n_L. Assuming that the $SU(2)_R$ breaking scale is $\sim 10^{2.5}$ that of $SU(2)_L$, $m_\nu \sim 0.1$ eV suggests $m_n \sim 10$ keV. It is thus a very suitable candidate for warm dark matter, which is a possible new paradigm for explaining the structure of the Universe at all scales. Matter and dark matter both have baryon and lepton numbers and follow parallel paths as the Universe expands. Both are produced with a $B-L$ asymmetry in the early Universe and their remnants are the u and d quarks, the electron, three neutrinos as well as three scotinos.

Just as neutrinos are very difficult to see because they interact so weakly, the scotinos are much more so. The only chance may be the production of the lightest exotic h quark at the LHC. Its decay is predicted to be completely semileptonic. This model also predicts two Higgs doublets, with one coupling to d quarks, and the other to u quarks and charged leptons. As more LHC data become available, it may be possible to test these specific predictions.

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