Flipping principle for neutrino mass and dark matter

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Flipping a symmetry often leads to a more fundamental symmetry and new physics insight. Applying this principle to the standard model electroweak symmetry, we obtain a novel gauge symmetry, which defines dark charge besides electric charge, neutrino mass mechanism, and resultant dark parity as residual flipped symmetry. The dark parity divides the model particles into two classes: odd and even. The dark matter candidate transforms as a fermion or a scalar singlet, having a mass below the electron mass, being stabilized by the dark parity. Scenarios for consistent neutrino mass generation and dark matter relic are proposed.

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The idea of flipping a symmetry leading to a relevant new physics is not new, but its principle has not explicitly been studied. Further, the implication of flipped symmetry has not significantly been studied.

Take, for instance, the SU(2)L symmetry of weak isospin T_{1,2,3} in the V–A theory \[1–3\]. The matter content transforms as isodoublets \( l_L = (\nu_L, e_L) \) and \( q_L = (u_L, d_L) \). The key for flipping SU(2)L lies at the electric charge (Q). Indeed, the electric charge of multiplets is determined as \( Q = \text{diag}(0, -1) \) for \( l_L \) and \( Q = \text{diag}(2/3, -1/3) \) for \( q_L \). This yields \( Q, T_1 \pm i T_2 = \pm (T_1 \pm i T_2) \neq 0 \) and \( \text{Tr} Q \neq 0 \). Thus, \( Q \) neither commutes nor closes algebraically with \( T_{1,2,3} \). The nonclosure requires SU(2)L flipped (i.e. enlarged) to SU(2)L \( \otimes U(1)_Y \) by symmetry principles, called gauge completion, where \( Y \equiv Q – T_3 \) is a new Abelian charge, well-known hypercharge. A new observation is that since \( T_3 \) is gauged, \( Q \) and \( Y \) must simultaneously be gauged as a result of noncommutation. Hence, the flip leads to electroweak theory \[4–9\], predicting the neutral current and the need of right-handed fermion singlets \( e_R, u_R \), and \( d_R \) for canceling the \( U(1)_Y \) anomalies.

Now a curious question is that can neutrino mass and dark matter be flipped from SU(2)L too? Since the electric charge is theoretically not fixed \[7–10\], we suppose a variant of it, called dark charge (\( D \)), such that \( D = \text{diag}(1, 0) \) for \( l_L \) and \( D = \text{diag}(1/3, -2/3) \) for \( q_L \). The dark charge for the Higgs doublet \( \phi = (\phi^+, \phi^0) \) is \( D = \text{diag}(1, 0) \), which is assigned so that \( D \) is not broken by the electroweak vacuum. Analogous to \( Q \), the dark charge \( D \) neither commutes nor closes algebraically with SU(2)L, which yields, by the flipping principle, a novel gauge symmetry \( SU(2)_L \otimes U(1)_Y \otimes U(1)_N \), where \( N \equiv D – T_3 \). Because the charges \( Y \) and \( N \) are independently linear, the full gauge symmetry takes the form,

\[ SU(2)_L \otimes U(1)_Y \otimes U(1)_N, \]

apart from the QCD group. Besides the mentioned fermion singlets, the right-handed neutrino \( \nu_R \) is now required to cancel the [Gravity]2U(1)N anomaly. It is checked that all the other anomalies vanish too. For comparison, the \( Q \) and \( D \) charges are collected in Table I while the SU(2)L representations and \( Y, N \) charges are supplied in Table II. Here, the singlet scalar \( \chi \) is necessarily included to break \( U(1)_N \) symmetry and generate right-handed neutrino mass\[2\].

\[\begin{array}{c|cccccccc}
\hline
\text{Field} & \nu & e & u & d & \phi^+ & \phi^0 & \chi \\
\hline
Q & 0 & 1/2 & 2/3 & -2/3 & 1 & 0 & 0 \\
D & 1 & 0 & 1/3 & -2/3 & 1 & 0 & -2 \\
\hline
\end{array}\]

TABLE I. \( Q \) and \( D \) charges of the model particles.

| Multiplet | \( l_L \) | \( q_L \) | \( e_R \) | \( d_R \) | \( \phi \) | \( \chi \) |
|-----------|----------|----------|----------|----------|----------|----------|
| SU(2)L    | 2        | 2        | 2        | 2        | 2        | 1        |
| Y         | -1/2     | 1/6      | 0        | -1/2     | -1/3     | 1/2      |
| N         | 1/2      | -1/6     | 1        | 0        | 1/3      | -2/3     |

TABLE II. SU(2)L, \( Y \), and \( N \) quantum numbers of the model multiplets.

The \( U(1)_N \) symmetry must be broken at a high energy scale for the model consistency. This can be done when the scalars develop vacuum expectation values (VEVs), \( \langle \chi \rangle = \Lambda / \sqrt{2} \) and \( \langle \phi \rangle = (0, v) / \sqrt{2} \), such that \( \Lambda \gg v = 246 \) GeV. Thus, the scheme of gauge symmetry breaking is

\[\begin{array}{c|cccccccc}
\hline
\text{Field} & \nu & e & u & d & \phi^+ & \phi^0 & \chi \\
\hline
Q & 0 & 1/2 & -2/3 & 1/2 & 1 & 0 & 0 \\
D & 1 & 0 & 1/3 & -2/3 & 1 & 0 & -2 \\
\hline
\end{array}\]

\[\delta \equiv \Lambda / v \gg 1\]

\[2\] A general version of dark charge can be constructed in terms of arbitrary \( \delta \) parameter, in which \( D(\nu) = \delta \), \( D(e) = \delta – 1 \), \( D(u) = 2/3 – \delta / 3 \), \( D(d) = -1/3 – \delta / 3 \), and \( D(\chi) = -\delta \), for every both left- and right-handed fermion components \( f_{L,R} \). But, the present case \( \delta = 1 \) makes dark matter stability easily.

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1 Although generation indices are suppressed, three generations of fermions are always taken into account.
TABLE III. Dark parity of the model particles.

| Particle | $\nu$ | $e$ | $u$ | $d$ | $\phi^+$ | $\phi^-$ | $\chi$ | $W$ | $Z$ | $Z'$ |
|----------|------|-----|-----|-----|---------|---------|--------|----|----|-----|
| $D_P$    | 1    | −1  | 1   | −1  | 1       | 1       | 1      | 1  | 1  | 1   |

where the first step implies a dark parity $D'_P$ as a residual symmetry of $U(1)_N$, while the second step determines the electroweak symmetry breaking, as usual, and resultant dark parity $D_P$, which is a residual symmetry of $SU(2)_L \otimes U(1)_Y$ or $D = T_3 + N$. The dark parity transforms the component fields as $\Phi \rightarrow \Phi' = D_P \Phi$, where $D_P = e^{i\alpha D}$. It must conserve the $\chi$ vacuum, i.e. $D_P \Lambda = \Lambda$. (Note that $D$ always annihilates the $\phi$ vacuum, which need not be considered). We obtain $e^{\pm 2\alpha} = 1$, implying $\alpha = k\pi$ for $k = 0, \pm 1, \pm 2, \cdots$. Considering the residual symmetry for $k = \pm 3$, we get $D_P = (-1)^{3D}$. The dark parity is conveniently rewritten as

$$D_P = (-1)^{3(T_3 + N) + 2s} \quad (2)$$

after substituting $D = T_3 + N$ and multiplying the spin parity $(-1)^{2s}$, which is conserved by the Lorentz symmetry. The dark parity of particles is summarized in Table III, where $Z'$ is $U(1)_N$ gauge boson. Note that $\phi^\pm$ is a Goldstone boson eaten by $W^\pm$.

The electron is the lightest particle that is $D_P$ odd. We assume two candidates, a vector-like fermion ($n$) and a scalar ($\eta$), transforming under the gauge symmetry in equation (1) as

$$n \sim (1, 0, 2r), \quad \eta \sim (1, 0, 2r - 1), \quad (3)$$

for $r$ integer, which couple to $\nu_R$ through $y\bar{n}L\eta\nu_R$.\(^3\) The fields $n, \eta$ are all $D_P$ odd. They possess a mass $\mathcal{L} \supset -m_n\bar{n}n - m_\eta^2\eta^*\eta$, where $m_n^2 > 0$ may be shifted by an amount after symmetry breaking, since $\eta$ couples to other Higgs fields. One of them should be lighter than $e$, responsible for dark matter.\(^4\)

The model reveals a seesaw mechanism for neutrino mass generation. Indeed, the scalar singlet $\chi$ couples to $\nu_R$ through $\frac{1}{2}f^\dagger \nu_R^\dagger \nu_R$, yielding a large Majorana mass $m_R = -f^\dagger \Lambda / \sqrt{2}$ for $\nu_R$. Additionally, $\phi$ couples to both $l_L$ and $\nu_R$ through $h^\dagger \tilde{l}_L \phi \nu_R$, leading to a Dirac neutrino mass $m_D = -h^\dagger v/\sqrt{2}$. Applying the seesaw formula for $\Lambda \gg v$, this provides observed neutrino ($\sim \nu_L$) mass,

$$m_\nu \simeq -m_D m_R^{-1} \frac{v^2}{\sqrt{2} \Lambda}, \quad (4)$$

The heavy Majorana neutrino ($\sim \nu_R$) obtains a mass $\sim m_R$, retained at $\Lambda$ scale.

Large scale seesaw scenario. The predicted mass in (4) coincides with the observation, $m_\nu \sim 0.1$ eV, if

$$\Lambda \sim [(h^\nu)^2 / f^\nu] \times 10^{14} \text{GeV} \sim 10^{14} \text{GeV}, \quad (5)$$

which is proportional to the inflation scale driven by the $U(1)_N$ dynamics, where we assume $(h^\nu)^2 / f^\nu \sim 1$.[11,12]

This scenario can explain the baryon asymmetry via standard leptogenesis set by CP-violating decay of $\nu_R$ to normal matter $e\phi^+$.[13]

In the same manner, $\nu_R$ can decay CP-asymmetrically to a pair of dark matter $m^\eta$ through the $y$ coupling, explicitly written as $y_j\bar{n}_L\eta\nu_R$ for $j = 1, 2, 3$. The process is presented by Feynman diagrams in Fig. 1. Consider

$$\nu_R \rightarrow n + \eta$$

for the heavy Majorana mass matrix to be flavor diagonal, $m_R = \text{diag}(m_{\nu_{1R}}, m_{\nu_{2R}}, m_{\nu_{3R}})$, and hierarchical, $m_{\nu_{1R}} \ll m_{\nu_{2,3R}}$. The CP asymmetry parameter is evaluated as

$$\epsilon_{DM} = \frac{\Gamma(\nu_{1R} \rightarrow m^\eta) - \Gamma(\nu_{1R} \rightarrow \bar{n}^\eta^*)}{\Gamma(\nu_{1R} \rightarrow m^\eta) + \Gamma(\nu_{1R} \rightarrow \bar{n}^\eta^*)} \simeq -\frac{3}{16\pi y_1^3 y_1} \sum_{j \neq 1} \left[ (y_j^* y_j)^2 \right] \frac{m_{\nu_{2,3R}}}{m_{\nu_{1R}}}, \quad (6)$$

The observation $\Omega_{DM} \simeq 5 \Omega_B / \eta_{DM}$ leads to $m_{DM} / m_R \simeq 5 \eta_B / \eta_{DM}$, where $\eta_B = -(28/79)\eta_L$ is related to the usual

\(^3\) Especially, when $r = 0$ we need only introduce the left chiral component, $n_L$, since it does not contribute to the anomalies.

\(^4\) Hence, the dark matter candidate is stabilized by dark parity conservation, while the electron stability is always ensured by electric charge conservation, by contrast.
Taking where $\nu$ suppressed, in agreement with [16, 17]. In other words, mix, diphoton signals mediated by $\chi \sim m$ or scalar) dark matter mass to be $m_{\text{DM}} \sim 0.1$ MeV.

**Low scale seesaw scenario.** The predicted mass [4] yields a TeV seesaw scale, i.e. $\Lambda \sim \text{TeV}$, if $(h^\nu)^2/f^\nu$ is suitably small, e.g. $f^\nu \sim 0.1$ and $h^\nu \sim 10^{-6}$ similar to electron Yukawa coupling.

In this case $Z'$ and $\chi$ can be reached by particle colliders. The LEPII looks for $Z'$ boson via channel $e^+e^- \to \mu^+\mu^-$, constraining its mass and coupling to be $m_{Z'}/(g_N/2) > 6 \text{ TeV}$ [14]. Since $m_{Z'} \approx 2g_NA$, it follows that $\Lambda > 1.5 \text{ TeV}$. The LHC [15] searches for dilepton signals mediated by $Z'$, obtaining a mass bound 4 TeV for $Z'$ coupling similar to $Z$, which translates to a bound for $\Lambda$ analogous to the LEPII search. Since $\phi, \chi$ slightly mix, diphoton signals mediated by $\chi$ are appropriately suppressed, in agreement with [16 [17]. In other words, $\chi$ may pick up a mass at TeV.

The dark matter relic can be produced through a freeze-in mechanism [18] with narrow decay $\nu_{1R} \to n\eta^*$, where $\nu_{1R}$ and one of the two candidates (either $n$ or $\eta$) are in thermal equilibrium with standard model plasma. Note that the right-handed neutrino and the dark field in thermal equilibrium are always maintained by their gauge interaction with $Z'$, i.e. $\text{SM} + \text{SM} \leftrightarrow Z' \leftrightarrow \nu_{1R}\nu_{1R}$ (either $n\eta$ or $\eta^*$), respectively.

The decay rate is $\Gamma_{\nu_{1R}} = (y^2_{1R}/32\pi)m_{\nu_{1R}}$. Generalizing the result in [18], the relic density is

$$\Omega_{\text{DM}}h^2 \sim 0.1 \left( \frac{y_{1R}}{10^{-8}} \right)^2 \left( \frac{300 \text{ GeV}}{m_{\nu_{1R}}} \right) \left( \frac{m_{\text{DM}}}{0.1 \text{ MeV}} \right),$$

implying dark matter mass at 0.1 MeV for the correct density, $y_{1R} \sim 10^{-8}$, and the lightest right-handed neutrino with a 300 GeV mass.

To conclude, flipping a symmetry is necessarily determined by an extra noncommutative charge. This principle implies a dark charge, besides usual electric charge. The presence of dark charge leads to right-handed neutrinos, charged under dark charge, and they gain large Majorana masses due to dark charge breaking, not $B - L$ breaking. This produces small neutrino masses and resultant dark parity, implying a dark matter candidate lighter than electron. The flipped symmetry breaking scenario at large scale generates asymmetric dark matter with mass at 0.1 MeV, besides baryon asymmetry, both by standard leptogenesis. Whereas, the flipped symmetry breaking scenario at TeV scale recognizes freeze-in dark matter with mass at 0.1 MeV, governed by dark-dynamics, $U(1)_N$.

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\[ \text{In nonthermal leptogenesis, the right-handed neutrino produced by inflaton decay } \chi \rightarrow \nu_{1R}\nu_{1R}, \text{ the equality happens.} \]