Abstract

We propose a new realization of the one-loop radiative model of neutrino mass generated by dark matter (scotogenic), where the particles in the loop have an additional $U(1)_D$ gauge symmetry, which may be exact or broken to $Z_2$. This model is relevant to a number of astrophysical observations, including AMS-02 and the dark matter distribution in dwarf galactic halos.
The notion that dark matter (DM) is the origin of neutrino mass (scotogenic) is by now a common theme among many studies. The first one-loop realization \([1]\), as shown in Fig. 1, remains the simplest such example. The standard model (SM) of quark and lepton interactions is augmented by three neutral singlet Majorana fermions \(N_{1,2,3}\) and a second scalar doublet \((\eta^+, \eta^0)\). A new discrete \(Z_2\) symmetry is imposed so that the new particles are odd and all the SM particles even. The complex scalar \(\eta^0 = (\eta_R + i\eta_I)/\sqrt{2}\) is split by the allowed \((\lambda_5/2)(\Phi^\dagger\eta)^2 + H.c.\) term in the Higgs potential so that \(m_R \neq m_I\) and the scotogenic neutrino mass is given by \([1]\)

\[
(M_\nu)_{ij} = \sum_k \frac{h_{ik}h_{jk}M_k}{16\pi^2} \left[ \frac{m_R^2}{m_R^2 - M_k^2} \ln \frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2} \ln \frac{m_I^2}{M_k^2} \right].
\]

(1)

The DM candidate is either \(\eta_R\) (assuming of course that \(m_R < m_I\)) or \(N_1\) (assuming of course \(M_1 < M_{2,3}\)). Many studies and variations of this original model are now available in the literature. One important extension is the promotion of the stabilizing discrete \(Z_2\) symmetry to a \(U(1)_D\) gauge symmetry \([2, 3]\), which gets broken to \(Z_2\) through an additional scalar field. This has two effects: (1) the stability of dark matter is now protected against possible violation of the \(Z_2\) symmetry from higher-dimensional operators including those of quantum gravity, (2) the force carriers (both vector and scalar) between DM particles may be relevant in explaining a number of astrophysical observations.
Figure 2: One-loop generation of neutrino mass with $U(1)_D$ symmetry.

In this paper, we propose a new scotogenic model with a $U(1)_D$ gauge symmetry which may be exact or broken to $Z_2$. The new particles are two scalar doublets $(\eta_1^+, \eta_1^0) \sim 1$ and $(\eta_2^+, \eta_2^0) \sim -1$ under $U(1)_D$, and three neutral singlet Dirac fermions $N_{1,2,3} \sim 1$ under $U(1)_D$. The allowed couplings completing the loop, as shown in Fig. 2, are $h_1 \bar{N}_R \nu_L \eta_1^0$, $h_2 N_L \nu_L \eta_2^0$, and $(\Phi^t \eta_1) (\Phi^t \eta_2)$ which mixes $\eta_1^0$ and $\bar{\eta}_2^0$. Let

$$
\begin{pmatrix}
\eta_1^0 \\
\eta_2^0 
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\chi_1 \\
\chi_2
\end{pmatrix},
$$

(2)

where $\chi_{1,2}$ are mass eigenstates, then the analog of Eq. (1) becomes

$$(M_\nu)_{ij} = \sin \theta \cos \theta \sum_k \frac{[(h_1)_{ki}(h_2)_{kj} + (h_2)_{ki}(h_1)_{kj}]}{8\pi^2} M_k \left[ \frac{m_1^2}{m_1^2 - M_k^2} \ln \frac{m_1^2}{M_k^2} - \frac{m_2^2}{m_2^2 - M_k^2} \ln \frac{m_2^2}{M_k^2} \right],
$$

(3)

where $m_{1,2}$ are the masses of $\chi_{1,2}$ and $M_k$ the mass of $N_k$. Note that in contrast to Fig. 1, Majorana neutrino masses are obtained in Fig. 2 even though only Dirac masses appear in the loop. At this point, the $U(1)_D$ gauge symmetry may remain exact, in which case there is a massless dark photon. However, we can also break the $U(1)_D$ gauge symmetry to $Z_2$ by a complex singlet scalar field $\zeta \sim 2$, in which case there is a massive dark photon $\gamma_D$ as well as a dark Higgs boson, both of which may be relevant in astrophysics as force carriers between DM particles.

If $U(1)_D$ is unbroken, only $N_1$ is a DM candidate because $\eta_{1,2}^0$ are not split in their real
and imaginary parts, which means that their interaction with nuclei through $Z$ exchange cannot be suppressed and thus ruled out by direct-search data as a possible DM candidate. In the presence of $U(1)_D$ breaking with the allowed $y_L \zeta^\dagger N_L N_L$ and $y_R \zeta^\dagger N_R N_R$ couplings, $N$ is no longer a Dirac fermion, but if these new terms are small, it may still be a pseudo-Dirac particle. At the same time, the $\zeta \eta^\dagger \eta_2$ coupling allows splitting of the real and imaginary parts of $\eta_{1,2}$.

There is yet another scenario, where the gauge $U(1)_D$ symmetry becomes an exact global $U(1)_D$ symmetry. This is accomplished if $\zeta$ is forbidden to couple to $N$ or $\eta_{1,2}$, by choosing for example $\zeta \sim 3$. The spontaneous breaking of the gauge $U(1)_D$ symmetry now results in a global $U(1)_D$ symmetry, under which only $N$ and $\eta_{1,2}$ transform. This means that dark Higgs is no longer a force carrier for the dark matter $N$, but the vector force carrier $\gamma_D$ remains and is no longer massless.

In the following we choose our DM candidate to be the lightest Dirac (or pseudo-Dirac) $N$ and investigate how it fits into the standard thermal WIMP (Weakly Interacting Massive Particle) paradigm. The dark photon $\gamma_D$ may be massless [4] in which case a realistic scenario would require $N$ to be heavier than about 1 TeV. If $U(1)_D$ is broken by $\zeta = (u + \rho + i\sigma)/\sqrt{2}$, where $u = \sqrt{2}\langle\zeta\rangle$, then $\gamma_D$ is massive together with $\rho$. In the following we will assume $u$ to be small compared to the decoupling temperature of $N$, in which case its relic abundance is determined by the unbroken theory, whereas at present, its interaction with ordinary matter is determined by the broken theory. In the early Universe, $NN$ would annihilate to $\gamma_D\gamma_D$ and $\zeta\zeta^*$. Since the dark scalar singlet $\zeta$ must mix with the SM Higgs doublet $\Phi$ in the most general scalar potential containing both, and the dark photon $\gamma_D$ may have kinetic mixing [5] with the SM photon, these processes will allow $N$ to have the correct thermal relic abundance to be a suitable DM candidate. Furthermore, for $\gamma_D$ and $\rho$ lighter than about 0.1 GeV, a number of astrophysical observations at present may be explained.
Our DM scenario assumes \( N \) to be much heavier than the \( U(1)_D \) breaking scale. Thus \( N \) is in general pseudo-Dirac. As far as relic abundance is concerned, it behaves as a Dirac fermion \([6]\). Further, since it can annihilate into scalars \((\zeta \zeta^*)\) or vectors \((\gamma_D \gamma_D)\) instead of just SM quarks and leptons, its cross section is not suppressed by fermion mass. Its thermally averaged s-wave annihilation cross sections to \( \gamma_D \gamma_D \) and \( \zeta \zeta^* \) are given by

\[
\langle \sigma(N \bar{N} \to \gamma_D \gamma_D)v \rangle = \frac{\pi \alpha_D^2}{M_1^2},
\]

\[
\langle \sigma(N \bar{N} \to \zeta \zeta^*)v \rangle = \frac{(|y_L|^2 + |y_R|^2)^2 - (y_L y_R^* - y_R^* y_L)^2}{16 \pi M_1^2},
\]

where \( \alpha_D = g_D^2/4\pi \) is the dark fine structure constant and we have neglected the masses of \( \gamma_D \) and \( \zeta \).

Figure 3: Values of DM couplings \( \alpha_D \) (left) and \( y_L, y_R \) (right) as a function of DM mass required to obtain observed relic abundance of DM in the Universe. For simplicity we have chosen \( y_L = y_R \).

In Fig. 3 we display the values of DM couplings required to obtain the observed value for the dark-matter relic density of the Universe, \( \Omega_{DM} h^2 = 0.1187(17) \) \([7]\). For example, if \( M_1 = 1 \) TeV, then we need either \( \alpha_D = 0.04 \) or \( y_L = y_R = 0.48 \).

As \( U(1)_D \) is broken, the Dirac DM fermion \( N \) splits up into two Majorana fermions of about equal mass, The heavier state \( \Sigma_2 \) will decay into the lighter state \( \Sigma_1 \) and a force carrier \((\Sigma_2 \to \Sigma_1 \gamma_D, \Sigma_1 \rho)\) if kinematically allowed. If the mass splitting is smaller than the mass of
the force carriers, $\Sigma_2$ will decay through an off-shell force carrier or $\eta_{1,2}$ to $\Sigma_1$ and a pair of SM leptons.

There are two important phenomenological implications of our $U(1)_D$ DM scenario. First, the large positron excess observed by PAMELA \cite{8,9} requires an enhancement of the DM annihilation cross section at present compared to what it was at the time of freeze-out. This may be accomplished \cite{10} by the inclusion of a new force in the dark sector, resulting in a Sommerfeld enhancement of the cross section from multiple exchange of the light force carrier. Recent AMS-02 results \cite{11} may also be explained \cite{12} in a similar way. In our case, since $\rho$ mixes with $h$ and $\gamma_D$ mixes with $\gamma$, their decays to $\mu^-\mu^+$ and $e^-e^+$ are ideal for such a purpose.

Second, DM self interactions change its density profile from the usual collisionless WIMP scenario. To reconcile the theoretical prediction with the present astronomical observation of the halos of dwarf galaxies, a rather large cross section per unit DM mass $\sim 1$ cm$^2$/g is required, and may be achieved \cite{13,14} with rather light force mediators, such as $M_1 = 1$ TeV and $m_{\rho,\gamma_D} \sim 4$ MeV, or $M_1 = 100$ GeV and $m_{\rho,\gamma_D} \sim 20$ MeV.

Finally, additional insight into DM candidates in our scenario may come from direct detection experiments. The current XENON100 limits \cite{15} are already sensitive to very small couplings corresponding to the mixing of the dark-force carriers with the appropriate SM bosons. For a benchmark value $10^{-10}$ for the coupling involved in the kinetic mixing of the dark photon with the SM photon, and for a 10-100 MeV dark force-carrier mass, XENON100 excludes self-interacting DM with a mass larger than $\sim 300$ GeV \cite{14}.

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