Deep Correlation Between Cosmic-Ray Anomaly and Neutrino Masses

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Abstract

The anomaly recently reported by the cosmic-ray measurements suggests that, if explained by the decay of dark matter particle, the decay source is closely linked up with the leptonic sector of the standard model. It is observed that, with a simple dimensional analysis, the lifetime of dark matter for the anomaly is expressed by the energy scale of neutrino masses. We present two scenarios in which these two matter at issue (the dark matter width and the tiny neutrino masses) stem from a single operator involving a gauge-singlet scalar field.
1 Introduction

The dark matter, which accounts for about 23% of the energy density in the present Universe [1], has been a great mystery in astrophysics, cosmology, and particle physics. While various theoretically-motivated candidates have been discussed for dark matter particle, its detailed nature is still un-revealed. Among experimental methods being performed, the flux observations of high-energy cosmic rays are expected to give important information on the dark matter which can be an extra source of fluxes through its annihilation or decay. The recent result from the PAMELA experiment [2] indicates the surplus of positron flux over the expected background in conventional astrophysics, and some non-standard source of energetic positrons in our galaxy is needed. The dark matter, which comes from new physics beyond the Standard Model (SM), has been examined as one of possible explanations of this anomalous behavior, though it was pointed out that the data may be fitted by the effect of nearby pulsars [3]. Subsequent comprehensive analysis suggests that the cosmic-ray anomaly can be well described if there exists a dark matter which decays mainly into charged leptons and has the width $\Gamma_{\text{DM}} \approx 10^{-26}/\text{sec}$ [4].

Another important problem in the SM is the origin of neutrino mass, much lighter than the other SM fermions. For Majorana neutrinos, the seesaw mechanism [5] naturally works to have tiny masses by the integration of high-energy degrees of freedom, which leads to a higher-dimensional operator suppressed by a heavy scale. The neutrino experimental data implies that the heavy mass scale is around the grand unification scale to have light Majorana masses of order eV. Alternatively, for Dirac neutrinos, there exist gauge-singlet fermions in low-energy theory and couple to the SM neutrinos through the Dirac mass operator. In this case, the mass scale should be suppressed by some mechanism, e.g. in a similar way to the mass hierarchy of SM fermions for which various approaches have been proposed in the literature.

In this letter, we point out a deep correlation between these two problems: the origins of dark matter and neutrino mass. In particular, we present two scenarios where the long lifetime of dark matter is directly determined by the smallness of neutrino masses. The dark matter decay and neutrino mass come from a single operator in low-energy effective theory, and therefore they are naturally related. The close connection to the neutrino sector is also plausible for the experimental result that the excess is observed for the positron fraction and not for other components in cosmic rays. We focus, in this letter, on the implication for particle physics and do not discuss detailed predictions of the cosmic-ray spectrum, as it is influenced by various astrophysics factors such as the propagation of cosmic rays in our galaxy [6].
2 Scaling relations for $\Gamma_{\text{DM}}$

The unstable dark matter is a reasonable explanation for the cosmic-ray anomaly \[7\]: the lifetime is much longer than the age of the Universe and the main decay channel contains positrons and electrons, not colored particles. In addition, a precise measurement of the total $e^+ + e^-$ flux has been performed by the Fermi Gamma-ray Space Telescope \[8\]. The observed positron flux may be significantly contaminated by that from decaying dark matter with a few TeV mass and the lifetime of $\mathcal{O}(10^{26})$ sec \[4\]. It is interesting to notice that these two physical numbers implies a scaling relation for the decay width of TeV-scale dark matter:

$$\Gamma_{\text{DM}} \simeq 10^{-26} / \text{sec} \simeq \left( \frac{1 \text{ TeV}}{\Lambda} \right)^4 \text{TeV}, \quad (2.1)$$

with $\Lambda \simeq 10^{16}$ GeV that indicates the existence of unification-scale dynamics behind the dark matter data. For instance, the above relation follows if there exists a fermionic dark matter particle with TeV mass and it decays to the SM sector through a 4-Fermi operator suppressed by $1/\Lambda^2$. Motivated by this observation, the phenomenological analysis and various construction of grand unified models ($\Lambda = M_{\text{GUT}}$) have been performed \[9\].

If the neutrino physics has some relevance to the dark matter, another interesting viewpoint is found. Namely, noticing that a typical mass scale of neutrinos indicated by oscillation experiments is $m_\nu \simeq 10^{-1}$ eV and numerically $(m_\nu/\text{TeV}) \simeq (\text{TeV}/M_{\text{GUT}})$, the dark matter decay width in (2.1) has a different expression

$$\Gamma_{\text{DM}} \simeq \left( \frac{m_\nu}{\Lambda} \right)^2 \text{TeV}, \quad (2.2)$$

where $\Lambda$ is around the unification scale. The new scaling relation (2.2) suggests that, in low-energy theory below $\Lambda$, there is an effective operator suppressed by $1/\Lambda$ which causes the dark matter decay and is closely related to the neutrino mass in light of the cosmic-ray anomaly.

Let us clarify the property of dark matter from which the relation (2.2) is deduced. In the SM extension with a dark matter field $X$, there are four types of dark matter depending on the statistics and electroweak charge. We assume that the TeV-mass dark matter couples to the SM lepton doublets $L$ through an effective operator relevant for neutrino masses. An electroweak singlet fermion such as right-handed neutrinos $\nu_R$ is

*There are other attempts on joining together the neutrino masses and the cosmic-ray anomaly from decaying dark matter \[10\].
an immediate candidate for this property. An non-singlet (and charge neutral) fermion can also couple to $L$ with a (composite) scalar in a higher-dimensional representation of electroweak symmetry. In both cases, one easily finds with a dimensional counting that the decay width of $X$ is roughly estimated as $\Gamma_X \sim m_\nu$, instead of $m_\nu^2$ given in (2.2), if the gauge invariant operator $LX\mathcal{O}$ is relevant for neutrino masses where $\mathcal{O}$ contains the SM Higgs and other scalar fields. Such a large width is not suitable for the cosmic-ray anomaly.

Another candidate of dark matter $X$ is a TeV-mass scalar field. With an appropriate hypercharge, it can contain a neutral component as the dark matter [11]. Both for Dirac and Majorana neutrinos, their masses are transformed non-trivially under the SM gauge symmetry and come from the operators $\bar{L}\nu_R\mathcal{O}'$ and $\bar{L}c\mathcal{O}''$ supplemented by vacuum expectation values (VEV) of $X$ and/or the SM Higgs, where $\mathcal{O}', \mathcal{O}''$ are (composite) scalar operators. Expanded around the vacuum, the effective scale $\Lambda$ in this case is given by these VEVs which are at most the electroweak scale. That clearly leads to a rapid decay of dark matter. On the other hand, when $X$ does not develop its VEV, the neutrino mass operators given above should be generated by integrating out the heavy $X$. In this case, the decay width $\Gamma_X$ is found to be larger than $m_\nu$ and not suited for the cosmic-ray anomaly.

In the end, the electroweak singlet scalar is found to be a reasonable candidate for the decaying dark matter with its width being given by Eq. (2.2). The singlet scalar $\phi$ has two important properties for the scaling relation to work: (i) it decays into the SM sector through a higher-dimensional operator (and other decay vertices are suppressed) and (ii) it develops a non-vanishing VEV which induces neutrino mass from that operator. The dark matter filled in our Universe is the quantum fluctuation about the VEV:

$$\phi = \langle \phi \rangle + \phi_{\text{DM}}.$$  (2.3)

The cosmic-ray anomaly gives us a signal that $\langle \phi \rangle$ is around the unification scale and $\phi_{\text{DM}}$ has a TeV-scale mass in the vacuum. That is not unnatural, e.g. in supersymmetric theory which would help the dark matter scalar to realize a stabilized flat potential for a large VEV and to receive soft supersymmetry breaking for a small mass. Another way to incorporate a tiny mass/VEV ratio is to consider the dark matter as a Nambu-Goldstone field, as will be discussed later. In any case, the dark matter couples to the lepton sector via an effective operator for neutrino masses and the excess of positron fraction is naturally explained.
3 Decay from neutrino mass

There are two cases (two effective operators) for neutrino masses where the relation \( (2.2) \), i.e. the dark matter property described above, is encoded. The types of effective operators depend on whether neutrinos are Dirac or Majorana particles. While the present status of neutrino experiments does not discriminate between these operators, different theoretical frameworks beyond the SM are constructed according to it.

We first consider the Dirac neutrinos, namely introduce light right-handed neutrinos \( \nu_R (\nu_R = P_R \nu_R) \) in addition to the dark matter scalar \( \phi \). This model has the lepton number symmetry even after the condensations of dark matter and Higgs fields. The gauge-invariant operator for neutrino masses is given by

\[
\mathcal{L}_D^{\text{Dirac}} = -\frac{y}{M} \phi \bar{H}^\dagger \tau_R L + \text{h.c.,}
\]

(3.1)

where \( H \) is the SM Higgs field (\( \bar{H} = e^{iH^*} \)) and \( L \) is a lepton doublet (\( L = P_L L \)). The \( \phi \) dependence could be fixed by symmetry argument and/or high-energy dynamics at \( M \), but its detail is found to be almost irrelevant to the dark matter physics (see below). Inserting the expectation values of \( \phi \) and \( H \) [Eq. (2.3) and \( \langle H \rangle = (0, v/\sqrt{2}) \)], we obtain the Dirac mass \( m_\nu \) for neutrinos \( \nu = \nu_L + \nu_R \);

\[
m_\nu = \frac{y v \langle \phi \rangle}{\sqrt{2} M}.
\]

(3.2)

Expanded around the vacuum, the Lagrangian (3.1) is rewritten as

\[
\mathcal{L}_D = -m_\nu \left( 1 + \frac{h}{v} \right) \bar{\nu} \nu - m_\nu \left( 1 + \frac{h}{v} \right) \left( \phi_R \bar{\nu} \nu - \phi_I \bar{\nu} \gamma_5 \nu \right),
\]

(3.3)

where \( h \) is the Higgs boson and \( \phi_{\text{DM}} = \phi_R + i \phi_I \). We have taken \( \langle \phi \rangle \) and \( m_\nu \) to be real with suitable phase rotations. It is interesting to find from this Lagrangian that the dark matter decay is governed by only two quantities, \( \langle \phi \rangle \) and the dark matter mass \( m_{\text{DM}} \), and is independent of the model parameters \( y \) and \( M \) which are just utilized to have a proper scale of neutrino masses. This fact holds, namely the Lagrangian (3.3) is almost invariant, even if the dark matter dependence in the operator (3.1) is replaced with an arbitrary function \( Y(\phi) \). All decay amplitudes are multiplied by a single common factor \( \partial \ln Y(\langle \phi \rangle) / \partial \ln \langle \phi \rangle \).

The dominant decay of dark matter occurs through the second term in (3.3) and is given by the (lepton number conserving) 2 and 3-body decays at tree level: \( \phi_{\text{DM}} \rightarrow \nu \bar{\nu} \) and \( \nu \bar{e}W, \nu \bar{\nu}Z, \nu \bar{\nu}h \). The decay vertices are fixed by the ratio \( m_\nu / \langle \phi \rangle \) and the expectation value \( \langle \phi \rangle \) plays the role of \( \Lambda \) in the scaling relation discussed in the previous section. We
find the partial decay widths

\[ \Gamma_{\nu \bar{\nu}} = \frac{m_{DM}^2}{8\pi} \frac{m_\nu^2}{\langle \phi \rangle^2}, \quad \Gamma_{\nu W} \simeq \Gamma_{\nu Z} \simeq \Gamma_{\nu h} \simeq \frac{m_{DM}^3}{768\pi^3 v^2} \frac{m_\nu^2}{\langle \phi \rangle^2}. \] (3.4)

For the latter formula, we have dropped the sub-leading terms suppressed by \( v^2/m_{DM}^2 \). In the SM language, the above chirality-violating decays are caused by the neutrino Yukawa and electroweak dipole operators accompanied by the dark matter scalar. The 3-body decays are comparable to the 2-body one, since the phase space suppression is supplemented with the enhancement factor \( m_{DM}^2/v^2 \). The decay widths become

\[ \Gamma_{\nu \bar{\nu}} \simeq 1.8 \times 10^{-26}/\text{sec}, \quad \Gamma_{3\text{-body}} \simeq 0.3 \times 10^{-26}/\text{sec}, \] (3.5)

for typical values \( m_\nu = 10^{-1} \text{ eV}, m_{DM} = 3 \text{ TeV}, \) and \( \langle \phi \rangle = 10^{16} \text{ GeV} \). The positrons are emitted by one of the 3-body decays, \( \phi_{DM} \to \nu eW^- \), and the cosmic-ray anomaly observed by the PAMELA experiment indicates the dark matter with a few TeV mass and an expectation value \( \langle \phi \rangle \) of the unification scale. That is exactly what we infer from the scaling relation (2.2).

Another case is the Majorana neutrino. The seesaw mechanism leads to tiny neutrino masses by integrating out heavy right-handed fermions. The Lagrangian relevant for neutrino masses is given by

\[ \mathcal{L}_M = -y \bar{\nu}_R \nu_R L - \frac{f}{2} \phi \bar{\nu}_R \nu_R + \text{h.c.}, \] (3.6)

where \( y \) is the neutrino Yukawa coupling and \( \nu_R^c \) denotes the charge-conjugate spinor. Similar to the Dirac neutrino case, the couplings \( y \) and \( f \) are not directly relevant to the dark matter physics. This model has the conserved lepton number if a suitable charge is assigned to the dark matter scalar \( \phi \) and it is broken in the vacuum. The expectation value \( \langle \phi \rangle \) gives the Majorana mass of right-handed neutrinos: \( m_R = f \langle \phi \rangle \). The integration of heavy modes \( (m_R \gg m_{DM}) \) induces an effective operator between the dark matter and SM fields:

\[ \mathcal{L}_M = \frac{y^T y}{f^* \phi^*} \overline{L}_R \phi^* \bar{H}^* \bar{\nu}_R \nu_R + \text{h.c.}. \] (3.7)

\[ \text{†The Nambu-Goldstone boson from broken lepton number symmetry has been discussed as a dark matter candidate in different contexts [12].} \]

\[ \text{‡If right-handed neutrinos are lighter than the dark matter, the decay width is proportional to } f^2 \text{ or } f m_\nu/(\langle \phi \rangle) \text{, depending on } m_R. \text{ For both cases, the cosmic-ray anomaly implies a too small } f, \text{ in other words, a trans-Planckian value of } \langle \phi \rangle \text{ is needed unless } m_R < (M_{Pl}/M_{GUT}) m_{DM}. \]
Inserting the expectation values of $\phi$ and $H$, we obtain the seesaw-induced Majorana mass $m_\nu$ for light neutrinos $\nu = \nu_L + \nu_L^c$:

$$m_\nu = -\frac{y^T y v^2}{m_R^2}.$$  \hspace{1cm} (3.8)

Expanded around the vacuum, the Lagrangian (3.7) is rewritten as

$$\mathcal{L}_M = -\frac{1}{2} m_\nu \left( 1 + \frac{h}{v} \right)^2 \bar{\nu} \nu + \frac{m_\nu}{2} \left( 1 + \frac{h}{v} \right)^2 (\phi_R \bar{\nu} \nu + \phi_I \bar{\nu} i\gamma_5 \nu) + \mathcal{O}(\phi_{DM}^2),$$  \hspace{1cm} (3.9)

where $h$ is the Higgs boson and $\phi_{DM} = \phi_R + i\phi_I$. We have assumed that $\langle \phi \rangle$ and $m_\nu$ are made real by phase rotations. Notice that the Lagrangian is very similar to that in the Dirac neutrino case, except that $\nu$ is a Majorana particle. The dark matter decay via the operator (3.7) is governed by $\langle \phi \rangle$ and $m_{DM}$, and is independent of the Yukawa couplings. This fact holds even if the dark matter dependence in (3.6) is replaced with an arbitrary function $F(\phi)$. All decay amplitudes with the seesaw operator are multiplied by a single common factor $\partial \ln F(\langle \phi \rangle)/\partial \ln \langle \phi \rangle$.

The dark matter decay through the operator (3.7) occurs in the exactly same fashion as the Dirac neutrino case with the replacement $\nu_R \rightarrow \nu_L^c$. The second terms in (3.9) therefore lead to the (lepton number violating) 2 and 3-body decays at tree level: $\phi_{DM} \rightarrow \nu \bar{\nu}$ and $\nu \bar{\nu} W, \nu \bar{\nu} Z, \nu \bar{\nu} h$, and the partial decay widths are respectively given by Eq. (3.4). The decay vertices are fixed by the ratio $m_\nu/\langle \phi \rangle$ and the expectation value $\langle \phi \rangle$ is around the unification scale so that the scaling relation is concluded irrespectively of other coupling constants. These chirality-violating decays are brought about by the Yukawa and electroweak dipole operators. On the other hand, there are several chirality-conserving operators generated at 1-loop level. They include $\phi_{DM}|H|^2$, $\phi_{DM}|D_\mu H|^2$, and $\phi_{DM} L \gamma^\mu D_\mu L$, where $D_\mu$ means the electroweak covariant derivative. The former two types of operators induce the decays into two electroweak bosons, $\phi_{DM} \rightarrow W^+ W^-, ZZ, hh$, and tend to be the main decay modes. These decays would cause an undesirable anti-proton excess in cosmic ray as well as positrons but are all forbidden by identifying the imaginary part $\phi_I$ with the dark matter. The last leptonic operator gives rise to the decay into a pair of charged leptons or neutrinos whose amplitude, due to the chirality conservation, receives a helicity suppression to an unobservable level. The last operator also induces chirality-preserving 3-body decays, e.g. $\phi_{DM} \rightarrow \nu \bar{\nu} W$. While they are suppressed by the 1-loop factor of electroweak gauge coupling, the necessary chirality flip in the loop gives an enhancement factor $m_R/\text{TeV}$ which makes

\footnote{For the Dirac neutrino case, such operators are not induced to the extent that the tree-level result is affected, because of tiny chirality-flip mass parameters.}
the loop contribution important for heavier right-handed neutrinos. The partial width of loop-level decay is roughly given by \( \Gamma_{\text{loop}} \sim (m_\nu/\langle \phi \rangle)^2 m_{R}^5 m_{DM}^2/(8\pi^2 v^2)^3 \) and would be dominant for \( m_R \gtrsim O(10) \) TeV.

We finally mention a hybrid of the two models: the Lagrangian for neutrino masses and dark matter scalar is given by

\[
\mathcal{L}_H = -\frac{y}{M} \phi \tilde{H}^\dagger \nu_R^T L + \frac{m_R}{2} \nu_R^T \epsilon \nu_R + \text{h.c.} \quad (3.10)
\]

For a negligible order of \( m_R \), this model reduces to the Dirac neutrino case. In another situation with \( m_R \gtrsim O(1) \) eV, the seesaw operation should be viable and the model is similar to the Majorana neutrino case. The only difference is that, for lighter \( \nu_R \) than the dark matter, the decay width is suppressed by \( m_\nu/m_R \) compared with the Majorana case. This fact could help the model by decreasing the parameter region of a huge value of \( \langle \phi \rangle \).

Several comments on phenomenology and high-energy dynamics are made in order:

(i) Leptonic decay: The cosmic-ray observation suggests that the dark matter interaction is leptonic and the scaling relation implies that the dark matter is neutrino-involving. That is clearly seen in the Majorana neutrino case: the SM gauge invariance ensures that the dark matter scalar can only couple to the matter sector via right-handed neutrinos at the renormalizable level. The lepton number symmetry also provides this picture with an attractive support. As for the Dirac neutrino case, an extra (discrete) symmetry might be needed not to have an anomalous excess of anti-proton flux. For example, the dark matter and right-handed neutrinos are charged under such a symmetry so that the combination \( \phi^* \nu_R \) becomes singlet. An interesting possibility is the higher-dimensional theory in which only right-handed neutrinos propagate in the bulk \([14]\) and the dark matter is supplied by a moduli field associated with the extra-dimensional space such as the radion. The translational invariance ensures that it couples to the SM sector only through the neutrino Yukawa term (the leading bulk-boundary interaction) and hence decays into the leptonic modes. Furthermore the neutrino mass and the decay rate of dark matter could be made tiny by the volume suppression factor from the extra space.

(ii) Dark matter symmetry: The effective mass operator \( (3.11) \) can be described in a similar way to the other SM fermions masses. For example, it is extended to a polynomial form \( Y(\phi) = y(\phi/M)^n \) (and hence the decay width is multiplied by \( n^2 \)). The exponent \( n \) is determined by high-energy dynamics above \( M \) such as the Froggatt-Nielsen mechanism \([13]\) with \( U(1) \) symmetry under which the dark matter scalar is charged. Such a symmetry is
also responsible for avoiding a rapid decay of this Froggatt-Nielsen dark matter via a coupling to the SM Higgs of the form $\phi|H|^2$. Furthermore, if the dark matter is identified with the imaginary component $\phi_I$, its Nambu-Goldstone nature from the broken $U(1)$ symmetry makes it natural to have a much smaller mass than the (unification-scale) expectation value. Such property of dark matter is also true for the Majorana neutrino case: the lepton number symmetry plays the same role as the Froggatt-Nielsen symmetry. One may wonder whether, if such symmetry were anomalous, that induces a loop-level decay of dark matter $\phi \rightarrow W^+W^-$ etc. through a dimension-five anomaly operator $\epsilon^{\mu\nu\rho\sigma} \phi D_\mu W^\nu_\nu D_\rho W^\sigma_\sigma$ which would lead to an excess of the anti-proton flux as well as the positron. However this is not the case for the present two scenarios: the anomaly operator coefficient is suppressed by small left-right mixing and becomes negligible. For the Dirac neutrino case, the partial width of anomalous decay is proportional to $m_\nu^2/\langle \phi \rangle^2$ and for the seesaw case, the amplitude is found to be proportional to $m_\nu/m_R^2$, i.e. the decay occurs through a dimension-seven operator $\epsilon^{\mu\nu\rho\sigma} \phi (D_\mu D_\nu H) \dagger D_\rho D_\sigma H$ in low-energy effective theory.

(iii) **Relic abundance**: A gauge-singlet scalar has a renormalizable interaction to the SM sector via $|\phi|^2|H|^2$. (As mentioned above, the $\phi|H|^2$ term is absent if $\phi$ has a nonzero charge of some symmetry.) In appropriate regime of parameter space, it provides a natural explanation of the relic abundance of dark matter in the present Universe [15]. Since $|\phi|^2 = (\phi_R + \langle \phi \rangle)^2 + \phi_I^2$, the imaginary component is interpreted as the dark matter and the real part has already decayed in the early Universe.

4 Summary

To summarize, we have pointed out a deep connection between the neutrino and dark matter physics in light of the recently observed cosmic-ray anomaly and presented two scenarios, as it were, the Froggatt-Nielsen dark matter and the seesaw dark matter, where a single effective operator involving the gauge-singlet scalar produces correlated sizes of neutrino masses and the dark matter lifetime. While the form of effective operator and typical scales of coupling constants would be dictated by high-energy dynamics, its details are almost irrelevant to the dark matter decay.

The scenarios described in this paper have an important prediction on future neutrino telescopes [16]. When the dark matter mass is $O(1)$ TeV, the neutrino pair production is the main decay mode and its branching ratio is about ten times larger than that for charged leptons. This will be an smoking-gun signature to confirm that the cosmic-ray anomaly comes from the decay of dark matter, since the signal is observed as a neutrino
flux with a monochromatic spectrum. It is also important to evaluate the anti-proton and
gamma-ray fluxes caused by the dark matter decay from which the weak gauge bosons are
produced in addition to the charged leptons. A recent analysis [17] of similar decay modes
such as $\text{DM} \to eW$ and $\text{DM} \to \mu W \to e\nu\bar{\nu}W$ shows that, depending on the diffusion
parameters, the scenario would be constrained by the measurements of anti-proton flux at
the PAMELA [18] and the diffused gamma ray at the Fermi-LAT [19]. These astrophysical
examination are important for corroborating the scenarios and the scaling relation.

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