

Scalar dark matter, Type II Seesaw and the DAMPE cosmic ray $e^+ + e^-$ excess

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The Dark Matter Particle Explorer (DAMPE) has reported a measurement of the flux of high energy cosmic ray electrons plus positrons (CREs) in the energy range between 25 GeV and 4.6 TeV. With unprecedented high energy resolution, the DAMPE data exhibit an excess of the CREs flux at an energy of around 1.4 TeV. In this letter, we discuss how the observed excess can be understood in a minimal framework where the Standard Model (SM) is supplemented by a stable SM singlet scalar as dark matter (DM) and type II seesaw for generating the neutrino mass matrix. In our framework, a pair of DM particles annihilates into a pair of the SM SU(2) triplet scalars (Δ s) in type II seesaw, and the subsequent Δ decays create the primary source of the excessive CREs around 1.4 TeV. The lepton flavor structure of the primary source of CREs has a direct relation with the neutrino oscillation data. We find that the DM interpretation of the DAMPE excess determines the pattern of neutrino mass spectrum to be the inverted hierarchy type, taking into account the constraints from the Fermi-LAT observations of dwarf spheroidal galaxies.

The Dark Matter Particle Explorer (DAMPE) has reported a new measurement of the flux of high energy cosmic ray electrons plus positrons (CREs) in the energy range of 25 GeV-4.6 TeV [1]. This experiment has an excellent performance for the CREs energy resolution at the TeV scale and a high power of the hadron rejection. The DAMPE data exhibit not only a spectral break around 0.9 TeV, which was indicated by the H.E.S.S. experiments [2], but also display an intriguing excess at an energy of around 1.4 TeV.

The DAMPE excess in the CREs spectrum has already stimulated a number of proposals for particle physics interpretations through pair annihilations of dark matter (DM) particles [3]. Since the excess is localized around 1.4 TeV, we may consider a pair of DM particles is mostly annihilating into leptons, namely, "leptophilic dark matter." In Ref. [4] (see also Ref. [5]), the authors have performed a model-independent analysis to fit the DAMPE excess with a variety of leptonic channels ($\ell^+\ell^-$ and 4ℓ , where $\ell = e, \mu, \tau$) from DM annihilations or late-time DM decays, along with the constraints from the Fermi-LAT observations of dwarf spheroidal galaxies [6, 7] and the Planck observations of Cosmic Microwave Background anisotropies [8]. It has been shown [4] that the Fermi-LAT observations disfavor the τ channels for the DM annihilation and the entire region for late-time DM decays. In addition, the interpretation with DM annihilations invokes a 'boost' factor which could either have an astrophysical origin (large inhomogeneities in the dark matter distribution), or have a particle physics origin such as the Sommerfeld enhancement [9, 10].

In this letter, we revisit a very simple extension of the SM in which two major missing pieces in the SM, namely, a dark matter candidate and the neutrino mass matrix, are incorporated. The model was proposed some years ago [11] to interpret an excess of cosmic ray positions reported by the PAMELA experiment [12]. More detailed analysis for the cosmic ray fluxes was performed in Ref. [13]. The DM particle in our scheme is a SM singlet scalar D [14], and its sta-

	SU(2) _L	U(1) _Y	Z ₂
ℓ_L^i	2	-1/2	+
H	2	+1/2	+
Δ	3	+1	+
D	1	0	-

TABLE I. Particle content relevant for our discussion in this letter. In addition to the SM lepton doublets ℓ_L^i ($i = 1, 2, 3$ being the generation index) and the Higgs doublet H , a complex scalar Δ and a real scalar D are introduced. The SM SU(2)_L triplet scalar Δ plays the key role in the type II seesaw mechanism, while D is the DM candidate.

bility is ensured by an unbroken Z_2 symmetry under which it carries negative parity. The leptophilic nature of this DM particle arises from its interactions with the SU(2) triplet scalar field (Δ) which is introduced to accommodate the observed neutrino oscillations [15] via the type II seesaw mechanism [17].

The particle content relevant for our discussion in this letter is summarized in Table I. An odd Z_2 parity is assigned to the SM singlet scalar (D), which makes it stable and a suitable DM candidate. It is often useful to explicitly express the triplet scalar by three complex scalars (electric charge neutral (Δ^0), singly charged (Δ^+) and doubly charged (Δ^{++}) scalars):

$$\Delta = \frac{\sigma^i}{\sqrt{2}} \Delta_i = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}, \quad (1)$$

where σ^i 's are Pauli matrices.

Following the notations of Ref. [16], the scalar potential

relevant for type II seesaw is given by

$$\begin{aligned}
V(H, \Delta) = & -m_H^2(H^\dagger H) + \frac{\lambda}{2}(H^\dagger H)^2 \\
& + M_\Delta^2 \text{tr}[\Delta^\dagger \Delta] + \frac{\lambda_1}{2}(\text{tr}[\Delta^\dagger \Delta])^2 \\
& + \frac{\lambda_2}{2}\left((\text{tr}[\Delta^\dagger \Delta])^2 - \text{tr}[\Delta^\dagger \Delta \Delta^\dagger \Delta]\right) \\
& + \lambda_4 H^\dagger H \text{tr}(\Delta^\dagger \Delta) + \lambda_5 H^\dagger [\Delta^\dagger, \Delta] H \\
& + [2\lambda_6 M_\Delta H^T i\sigma_2 \Delta^\dagger H + \text{H.c.}], \quad (2)
\end{aligned}$$

where the coupling constants λ_i are taken to be real without loss of generality. The triplet scalar (Δ) has a Yukawa coupling with the lepton doublets given by

$$\begin{aligned}
\mathcal{L}_\Delta = & -\frac{1}{\sqrt{2}}(Y_\Delta)_{ij} \ell_L^{Ti} C i\sigma_2 \Delta \ell_L^j + \text{H.c.} \\
= & -\frac{1}{\sqrt{2}}(Y_\Delta)_{ij} \nu_L^{Ti} C \Delta^0 \nu_L^j \\
& + \frac{1}{2}(Y_\Delta)_{ij} \nu_L^{Ti} C \Delta^+ e_L^j \\
& + \frac{1}{\sqrt{2}}(Y_\Delta)_{ij} e_L^{Ti} C \Delta^{++} e_L^j + \text{H.c.}, \quad (3)
\end{aligned}$$

where C is the charge conjugate matrix, and $(Y_\Delta)_{ij}$ denotes the elements of the Yukawa matrix.

A non-zero vacuum expectation value (VEV) of the Higgs doublet generates a tadpole term for Δ through the last term in Eq. (2). A non-zero VEV of the triplet Higgs is generated, $\langle \Delta^0 \rangle = v_\Delta / \sqrt{2} \simeq \lambda_6 v^2 / M_\Delta$, from minimizing the scalar potential. As a result, lepton number is spontaneously broken by Δ . From Eq. (3), this leads to the neutrino mass matrix:

$$m_\nu = v_\Delta (Y_\Delta)_{ij}. \quad (4)$$

Here v is the SM Higgs doublet VEV with $v^2 + v_\Delta^2 = (246 \text{ GeV})^2$.

Note that the triplet Higgs VEV contributes to the weak boson masses and alters the ρ -parameter from the SM prediction, $\rho = 1$, at tree level. The current precision measurement [15] constrains this deviation to be within the range, $\Delta\rho = \rho - 1 \simeq v_\Delta / v \lesssim 0.01$, so that we obtain $\lambda_6 \lesssim 0.01 M_\Delta / v$.

We can fix the structure of $(Y_\Delta)_{ij}$ by using the neutrino oscillation data:

$$Y_\Delta = \frac{1}{v_\Delta} U_{\text{MNS}}^* D_\nu U_{\text{MNS}}^\dagger, \quad (5)$$

where U_{MNS} is the neutrino mixing matrix in the standard form [15], and $D_\nu = \text{diag}(m_1, m_2, m_3)$ is the neutrino mass eigenvalue matrix. We employ the neutrino oscillation data: $\sin^2 2\theta_{13} = 0.092$ [18] along with $\sin^2 2\theta_{12} = 0.87$, $\sin^2 2\theta_{23} = 1.0$, $\Delta m_{12}^2 = m_2^2 - m_1^2 = 7.6 \times 10^{-5} \text{ eV}^2$, and $|\Delta m_{23}^2| = |m_3^2 - m_2^2| = 2.4 \times 10^{-3} \text{ eV}^2$ [15]. Motivated by the recent measurement of the Dirac CP -phase (δ_{CP}), we set $\delta_{CP} = 3\pi/2$ [19]. For simplicity, we choose the lightest neutrino mass to be zero. With $Y_\Delta \gtrsim v_\Delta / M_\Delta$, the triplet scalar Δ dominantly decays to a pair of leptons, such as $\nu^i \nu^j$,

$\nu^i e^j$, $e^i \nu^j$ and $e^i e^j$. With the oscillation data inputs, we calculate the ratio for the charged lepton flavors produced by the Δ decay ($\Delta \rightarrow \nu^i e^j$, $e^i \nu^j$, $e^i e^j$) to be

$$e : \mu : \tau \simeq 0.1 : 1 : 1 \quad (\text{Normal Hierarchy}), \quad (6)$$

$$e : \mu : \tau \simeq 2 : 1 : 1 \quad (\text{Inverted Hierarchy}), \quad (7)$$

for the neutrino mass patterns of normal hierarchy and inverted hierarchy, respectively. We find that these ratios are independent of the Majorana phases in U_{MNS} .

The scalar potential relevant for DM physics is given by

$$\begin{aligned}
V(H, \Delta, D) = & \frac{1}{2} m_0^2 D^2 + \lambda_D D^4 + \lambda_H D^2 (H^\dagger H) + \lambda_\Delta D^2 \text{tr}(\Delta^\dagger \Delta) \\
= & \frac{1}{2} m_D^2 D^2 + \lambda_D D^4 + \lambda_H v D^2 h + \frac{\lambda_H}{2} D^2 h^2 \\
& + \lambda_\Delta D^2 \left(\sqrt{2} v_\Delta \text{Re}[\Delta^0] + |\Delta^0|^2 + |\Delta^+|^2 + |\Delta^{++}|^2 \right) \quad (8)
\end{aligned}$$

where $m_D^2 = m_0^2 + \lambda_H v^2 + \lambda_\Delta v_\Delta^2$ is the DM mass, and h is the physical Higgs boson. Through the couplings λ_H and λ_Δ in this scalar potential, a pair of DM particles annihilates into pairs of the Higgs doublet and the triplet, $DD \rightarrow H^\dagger H$, $\Delta^\dagger \Delta$.¹ In order to evaluate the thermal DM relic abundance, we first calculate the thermally averaged cross section times relative velocity for the process in the non-relativistic limit, which is given by

$$\begin{aligned}
\langle \sigma v_{\text{rel}} \rangle = & \frac{1}{16\pi m_D^2} \left(\lambda_H^2 \sqrt{1 - \frac{m_h^2}{m_D^2}} + 6\lambda_\Delta^2 \sqrt{1 - \frac{M_\Delta^2}{m_D^2}} \right) \\
\simeq & \frac{1}{16\pi m_D^2} (\lambda_H^2 + 0.27\lambda_\Delta^2), \quad (9)
\end{aligned}$$

where we have chosen $m_h = 125 \text{ GeV}$ for the Higgs boson mass, $m_D - M_\Delta = 3 \text{ GeV}$ with $m_D = 3 \text{ TeV}$.

The present DM relic density is determined by solving the Boltzmann equation with the thermally averaged cross section in Eq. (9). We employ an approximation formula given by [20]

$$\Omega h^2 = \frac{1.07 \times 10^9 x_f \text{ GeV}^{-1}}{\sqrt{g_*} M_{\text{Pl}} \langle \sigma v_{\text{rel}} \rangle}, \quad (10)$$

where $M_{\text{Pl}} = 1.22 \times 10^{19} \text{ GeV}$ is the Planck mass, the freeze-out temperature $x_f = m_D / T_f$ is given by $x_f = \ln[X] - 0.5 \ln[\ln[X]]$ with $X = 0.038(1/g_*^{1/2}) M_{\text{Pl}} m_D \langle \sigma v_{\text{rel}} \rangle$, and we take $g_* = 100$ for the total degrees of freedom of the thermal plasma. We numerically find the solution,

$$\lambda_H^2 + 0.27\lambda_\Delta^2 \simeq 0.82, \quad (11)$$

to reproduce the observed DM relic density [8]

$$\Omega_{\text{DM}} h^2 \simeq 0.12. \quad (12)$$

¹ Although there are other DM annihilation processes such as $DD \rightarrow h \rightarrow W^+ W^-$, they are subdominant, since we choose $M_\Delta \gg v$ in the following.

The couplings in perturbative regime can satisfy Eq. (11).

Several experiments are underway to directly detect the DM particles through elastic scattering off nuclei. The most stringent limit on the spin-independent elastic scattering cross section has been obtained by the recent PandaX-II [21] experiment: $\sigma_{el} \leq 3 \times 10^{-9}$ pb for a DM mass of $m_D = 3$ TeV. This result leads to an upper bound on λ_H , since the scalar DM particle can scatter off a nucleon through processes mediated by the SM Higgs boson in the t -channel. The spin-independent elastic scattering cross section is given by

$$\sigma_{SI} = \frac{\lambda_H^2}{\pi m_h^4} \frac{m_N^2}{(m_N + m_D)^2} f_N^2, \quad (13)$$

where $m_N = 0.939$ GeV is the nucleon mass, and

$$f_N = \left(\sum_{q=u,d,s} f_{T_q} + \frac{2}{9} f_{TG} \right) m_N, \quad (14)$$

is the nuclear matrix element accounting for the quark and gluon contents of the nucleon. In evaluating f_{T_q} , we employ the results from the lattice QCD simulation [22]: $f_{T_u} + f_{T_d} \simeq 0.056$ and $|f_{T_s}| \leq 0.08$. To make our analysis conservative, we set $f_{T_s} = 0$. Using the trace anomaly formula, $\sum_{q=u,d,s} f_{T_q} + f_{TG} = 1$ [23], we obtain $f_N^2 = 0.0706 m_N^2$, and hence the spin-independent elastic scattering cross section is approximately given by

$$\sigma_{SI} = 3.2 \times 10^{-9} \text{ pb} \times \lambda_H^2, \quad (15)$$

for $m_h = 125$ GeV and $m_D = 3$ TeV. Hence, we find $\lambda_H^2 \leq 0.95$, which is not a strong constraint.

The dark matter in the halo of our galaxy can annihilate into the Higgs doublet and triplet. We choose $\lambda_H \ll \lambda_\Delta$, so that a pair of DM particles mainly annihilates into a pair of Δ , followed by the decay $\Delta \rightarrow \ell^i \ell^j$. In this way, the DM pair annihilations can produce 2 or 4 charged leptons. We recall here that due to the constraints from the Fermi-LAT observations, the τ channel is disfavored as a dominant final state. Therefore, the neutrino mass spectrum must exhibit inverted hierarchy from Eqs. (6) and (7). This is one of the main conclusions of this letter. To explain the DAMPE excess, we expect $m_D \simeq M_\Delta$, so that each final state lepton has almost a line spectrum. According to the fit results along with the Fermi-LAT constraints in Ref. [4], we set $m_D \simeq 3$ TeV and a small mass differences between D and Δ , as we have chosen in Eq. (9), to yield the energy of each lepton to be $E_\ell \simeq 1.5$ TeV. Our choice of $M_\Delta \simeq 3$ TeV satisfies the current lower bound [24], $M_\Delta \gtrsim 770\text{--}870$ GeV, from the search for doubly charged Higgs bosons at the Large Hadron Collider. To account for the DAMPE excess, the DM annihilation cross section is found to be much larger than the thermal cross section [4], and some enhancement mechanism is necessary. In the minimal version of our scenario, we simply assume that such an enhancement (boost factor) originates from large inhomogeneities in the dark matter distribution.

We may consider a particle physics origin for boosting the annihilation cross section of the DM particles. In Ref. [11],

a real scalar S , which is Z_2 -parity even and singlet under the SM gauge group, is introduced, and its mass is tuned to realize the Breit-Wigner enhancement for DM annihilations proposed in Ref. [25]. In this mechanism, the DM pair annihilation process in the present universe is enhanced through the s -channel resonance with an intermediate state. Although the same process is also relevant for DM annihilation in the early universe, a relative velocity between annihilating DM particles at the freeze-out time is not negligible, and the total energy of annihilating DM particles is away from the s -channel resonance pole. As a result, the annihilation cross section at the freeze-out time is suppressed, compared to the one at present.

As is well-known, the SM Higgs potential becomes unstable at high energies, since the running SM Higgs quartic coupling (λ in Eq. (2)) turns negative at the renormalization scale of $\mu = \mathcal{O}(10^{10})$ GeV [26]. However, it has been shown in Ref. [27] (before the Higgs boson discovery) that this electroweak vacuum instability can be solved in the presence of type II seesaw. See Ref. [28] for follow-up analysis after the Higgs boson discovery at the Large Hadron Collider.

In summary, motivated by the DAMPE cosmic ray $e^+ + e^-$ excess, we have revisited a simple extension of the SM to supplement it with neutrino masses via type II seesaw and a stable SM singlet scalar as the DM candidate. With a suitable choice of the couplings among the DM particles, the Higgs doublet and the triplet of type II seesaw, the DM particles in our galactic halo annihilate into a pair of triplet scalars, and their subsequent decays produce high energy CREs. Through the type II seesaw mechanism, the flavor structure of the primary leptons created by the triplet decay has a direct relation with the neutrino oscillation data. We have found that the DM interpretation of the DAMPE excess determines the pattern of neutrino mass spectrum to be the inverted hierarchy type, taking into account the constraints from the Fermi-LAT observations of dwarf spheroidal galaxies.

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