We study cosmic-ray anomaly observed by PAMELA based on $E_6$ inspired extra U(1) model with $S_4$ flavor symmetry. In our model, the lightest flavon has very long lifetime of $\mathcal{O}(10^{18})$ second which is longer than the age of the universe, but not long enough to explain the PAMELA result $\mathcal{O}(10^{26})$ sec. Such a situation could be avoidable by considering that the flavon is not the dominant component of dark matters. However non-thermalizing the flavon is needed to obtain proper relic density. This relates reheating temperature of the universe with seesaw mass scale. If we assume this flavon is a particle decaying into positron (or electron), the seesaw mass scale is constrained by reheating temperature. Thus we find an interesting result that the allowed region is around $\mathcal{O}(10^{12})$ GeV, which is consistent with our original result.
1 Introduction

It is one of the important task to build more economical models in (non-)Abelian flavor symmetries. In such the framework of models with non-renormalizable operators especially, couplings of the terms are usually suppressed by high energy cut-off scale. Therefore gauge singlet neutral bosons which couple to the term may play an important role not only to construct the mass matrix forms but also to be promising dark matter candidates, because they could be less-interactive enough. It is recently known that the dark matter can be a good candidate to explain PAMELA data [4]. Subsequently, there are many attempts to explain the positron anomaly by annihilation [2] or decay of the dark matter [3]. According to constraint from diffuse gamma ray [4], an interpretation by annihilation is almost excluded. Thus the PAMELA result is in favor of the decaying dark matter, when it has the life time of $\Gamma^{-1} \sim O(10^{20})$ sec. This is much longer than the age of the universe.

In this paper, we study such a cosmic-ray excess by a singlet scalar (flavon) in $S_4$ flavor model \(^{1}\) of a supersymmetric [5] with $E_6$ inspired extra $U(1)$ gauge symmetry [6]. The flavor symmetry is broken by vacuum expectation value (VEV) of the flavon and this VEV gives large Majorana masses for right handed neutrinos (RHNs). As the flavon couples to standard model particles only through non-renormalizable operators, the life time of the flavon could be longer than the age of the universe. However the life time of the flavon in our model is not longer than $O(10^{26})$ sec. Therefore we consider that the flavon is not the dominant component of dark matters. Then the most leading interaction which the flavon has is extra $U(1)_Z$ interaction and the interaction is extremely weak because it is suppressed by the large mass scale of the $U(1)_Z$ gauge boson. As the result, annihilation cross section is too small to obtain proper relic density of the flavon as long as we assume that the flavon is in thermal equilibrium. So we consider that the flavon is never in thermal equilibrium. Non-thermalizing the flavon constrains reheating temperature and also relates to right-handed neutrino mass scale. If we assume reheating temperature is constrained as $10^7 \text{ GeV} > T_{RH} > 10^4 \text{ GeV}$, right-handed neutrino mass scale should be around $10^{12} \text{ GeV}$, which is consistent with our original result.

The paper is organized as follows. In section 2, we review the basic structure of $S_4$ flavor symmetric extra $U(1)$ model. We evaluate density parameter of lightest flavon from PAMELA constraint in section 3, and estimate required right-handed neutrino mass scale for explaining it in section 4. Finally we make a brief summary in section 5.

2 The Extra $U(1)$ Model with $S_4$ Flavor Symmetry

2.1 The Extra $U(1)$ Model

The basic structure of the extra $U(1)$ model is given as follows [7]. At high energy scale, the gauge symmetry of model has two extra $U(1)$s, which consists maximal subgroup of $E_6$ as $G_2 = G_{SM} \times U(1)_X \times U(1)_Z \subset E_6$. MSSM superfields and additional superfields are embedded in three 27 multiplets of $E_6$ to cancel anomalies, as $27 \supset \{Q,U^c,E^c,D^c,L,N^c,H^D,g^c,H^U,g,S\}$, where $N^c$ are right-handed neutrinos (RHN), $g$ and $g^c$ are exotic quarks (g-quark), and $S$ are $G_{SM}$ singlets, which is illustrated in Table 1. We introduce $G_{SM} \times U(1)_X$ singlets $\Phi$ and $\Phi^c$ which develop the intermediate scale VEVs along the D-flat direction of $\langle \Phi \rangle = \langle \Phi^c \rangle$, then the $U(1)_Z$ is broken and the RHNs obtain the mass terms. After the symmetry is broken, as the R-parity symmetry remains unbroken, $G_1 = G_{SM} \times U(1)_X \times R$ survives at low energy. This is the symmetry of the low energy extra $U(1)$ model.

Within the renormalizable operators, $G_2$ symmetric superpotential is given as follows:

\begin{align*}
W_2 &= W_0 + W_S + W_B, \\
W_0 &= Y^U H^U Q U^c + Y^D H^D Q D^c + Y^E H^D L E^c + Y^N H^U L N^c + Y^M \Phi N^c N^c, \\
W_S &= k S g g^c + \lambda S H^U H^D, \\
W_B &= \lambda_1 Q Q g + \lambda_2 g^c U^c D^c + \lambda_3 g E^c U^c + \lambda_4 g^c L Q + \lambda_5 g D^c N^c.
\end{align*}

Where $W_0$ is the same as the superpotential of the MSSM with the RHNs besides the absence of $\mu$-term, and $W_S$ and $W_B$ are the new interactions. In $W_S$, $k S g g^c$ drives the soft SUSY breaking scalar squared mass of $S$ to negative through the renormalization group equations (RGEs) and then breaks $U(1)_X$ and

\(^{1}\)It requires exotic scalar quarks, which induce proton decay. In our original work [7], we have shown that proton decay is suppressed by $S_4$ flavor symmetry very well.
generates mass terms of g-quarks, and $\lambda_S H^U H^D$ is source of the effective $\mu$-term. Therefore, $W_0$ and $W_S$ are phenomenologically necessary. In contrast, $W_B$ leads to very rapid proton decay and must be forbidden. This is done by $S_4$ flavor symmetry.

### Table 1: $G_2$ assignment of fields. Where the $x$, $y$ and $z$ are charges of $U(1)_X$, $U(1)_Y$ and $U(1)_Z$, and $Y$ is hypercharge.

|    | $Q$ | $U^c$ | $E^c$ | $D^c$ | $L$ | $N^c$ | $H^D$ | $g^c$ | $H^U$ | $q$ | $S$ | $\Phi$ | $\Phi^c$ |
|----|-----|-------|-------|-------|-----|-------|-------|-------|-------|-----|-----|-------|-------|
| $SU(3)_c$ | 3   | 3* | 1   | 3* | 1 | 1 | 1 | 3* | 1 | 3 | 1 | 1 | 1 |
| $SU(2)_W$ | 2   | 1 | 1 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 1 | 1 |
| $y = 6Y$ | 1 | -4 | 6 | 2 | -3 | 0 | -3 | 2 | 3 | -2 | 0 | 0 | 0 |
| $x$ | 1 | 1 | 1 | 2 | 2 | 0 | -3 | -3 | -2 | -2 | 5 | 0 | 0 |
| $z$ | -1 | -1 | -1 | 2 | 2 | -4 | -1 | -1 | 2 | 2 | -1 | 8 | -8 |
| $R$ | - | - | - | - | - | - | - | + | + | + | + | + | + |

2.2 $S_4$ Flavor Symmetry

Non-Abelian group $S_4$ has two singlet representations 1, 1’, one doublet representation 2 and two triplet representations 3, 3’. where 1 is the trivial representation [8]. The most essential structure of $S_4$ group is that multiplication of two doublets does not contain triplets. With this property, if $g$ and $g^c$ are assigned to triplets and the others are assigned to singlets or doublets, then $W_B$ is forbidden.

The absence of $W_B$ makes g-quarks and proton stable, but the existence of g-quarks which have life time longer than 0.1 second spoils the success of Big Ban nucleosynthesis. In order to evade this problem, we assign $\Phi^c$ as triplet of $S_4$ and add the non-renormalizable terms:

$$W_{NRB} = \frac{1}{M_P^2} \Phi \Phi^c (Qg^c + g^c U^c D^c + g E^c U^c + g^c LQ + g^c D^c N^c).$$

(5)

When $\Phi^c$ develops VEV with

$$\frac{\langle \Phi \Phi^c \rangle}{M_P^2} \sim 10^{-12},$$

(6)

the phenomenological constraints on the life times of proton and g-quarks are satisfied at the same time [9], and the right-handed neutrino mass scale can be predicted as $M_R \sim \langle \Phi \rangle \sim 10^{-6} M_P \sim 10^{12}$ GeV.

As the flavons $\Phi$ and $\Phi^c$ which are the triggers of flavor violation do not have renormalizable interactions with light particles, the lightest flavon ($\mathcal{L}_F$) has very long life time. In following sections, we consider whether this particle explains PAMELA observation.

3 Flavon Decay Width

With the assignment that $\Phi^c$ is $S_4$ triplet and $\Phi$ is singlet or doublet, the leading term of flavon superpotential is given by

$$W_{\Phi} = \frac{a}{M_P} \Phi^2 (\Phi^c)^2.$$  

(7)

Solving the potential minimum conditions, we get

$$V = |\Phi| = |\Phi^c| \sim (m_{SUSY}/M_P/a)^{1/2} \sim 10^{11} a^{-1/2} \left(\frac{m_{SUSY}}{10 \text{ TeV}}\right)^{1/2} \text{ GeV},$$

(8)

where $a \sim 10^{-2}$ is required from Eq.(6). Integrating out the heavy RHNs, we get effective seesaw operators as follows

$$W_{eff} = \frac{1}{Y_{MN}} (Y^N H^U L)^2.$$  

(9)
Here we redefine flavon as perturbation around VEV as $\Phi \to V + \Phi$, then Eq.(9) is rewritten as
\[
W_{\text{eff}} = \frac{1}{Y^M V}(Y^N H^U L)^2 - \frac{\Phi}{Y^M V^2}(Y^N H^U L)^2.
\] (10)

If sleptons, squarks, g-quarks and scalar g-quarks are heavier than $\mathcal{L}\Phi$, this operator gives dominant contribution to decay width of $\mathcal{L}\Phi$ through
\[
\mathcal{L}_{\text{eff}} = \frac{m_\nu}{V} \Phi \nu \nu,
\] (11)
where we assume
\[
Y^M \sim 1, \quad m_\nu \sim \left(\frac{Y^N \nu}{V}\right)^2, \quad \langle H^U \rangle = \frac{v}{\sqrt{2}}.
\] (12)

From the interaction, monochromatic intense diffuse neutrino flux is expected in cosmic-ray at $E_\nu = \frac{m_\Phi}{2}$. It is an important signature of the decaying dark matter model. Considering the superpotential $W_\Phi$, it is easily shown that only one linear combination of six flavons $\Phi_{1,2,3}, \Phi^c_{1,2,3}$ has super heavy mass around $V$ and another five flavons have $O(M_{\text{SUSY}})$ masses. As is pointed in ref. [10], this interaction is good candidate for explaining PAMELA phenomena, because if $V$ is around $10^{16}$ GeV, then the partial decay width of $\Phi \to \nu H^- e^+$ is given by
\[
\Gamma^{-1}(\Phi \to \nu H^- e^+) = \left(\frac{m_\Phi^3}{68\pi^2 v^2 V^2}\right)^{-1} = 3.5 \times 10^{26} \text{ sec},
\] (13)
where
\[
m_\nu = 0.1 \text{ eV}, \quad v = 246 \text{ GeV}, \quad m_\Phi = 3 \text{ TeV}, \quad V = 10^{16} \text{ GeV}.
\] (14)

The result of Eq.(13) is in good agreement with ref. [3]. However, as $V \sim 10^{12}$ GeV in our model, the life time of $\mathcal{L}\Phi$ is not $10^{26}$ sec but $10^{18}$ sec. So we assume this $\mathcal{L}\Phi$ is not the dominant component of dark matter ($\Omega_{\mathcal{L}\Phi} \ll \Omega_{\text{DM}}$). Introducing mixing parameter $\epsilon$ defined as
\[
\Phi = \epsilon \Phi_{\mathcal{L}\Phi} + \cdots,
\] (15)
where $\Phi_{\mathcal{L}\Phi}$ is the lightest flavon field and the dots $\cdots$ means contributions from heavier flavons, the partial decay width of $\Phi_{\mathcal{L}\Phi} \to \nu H^- e^+$ is given by
\[
\Gamma^{-1}(\Phi_{\mathcal{L}\Phi} \to \nu H^- e^+) = 3.5 \times 10^{18} \epsilon^{-2} \left(\frac{V}{10^{12} \text{ GeV}}\right)^2 \text{ sec}.
\] (16)

In order to explain positron flux observed by PAMELA, density parameter of $\mathcal{L}\Phi$ should be
\[
\Omega_{\mathcal{L}\Phi} = \frac{\Gamma^{-1}(\Phi_{\mathcal{L}\Phi} \to \nu H^- e^+)}{10^{26} \text{ sec}} \Omega_{\text{DM}} = 3.9 \times 10^{-9} \epsilon^{-2} \left(\frac{V}{10^{12} \text{ GeV}}\right)^2 /h^2,
\] (17)
where we use the observed value of density parameter of dark matter in [11] as
\[
\Omega_{\text{DM}} = 0.11/h^2.
\] (18)

Before calculating density parameter of $\mathcal{L}\Phi$ in next section, we give some comments about possible decay channels of flavons. The interactions between flavons are described by
\[
\left(\frac{a}{M_P}\right)^2 V^3 \Phi_i \Phi_j \Phi_k \sim (10^{-4} \text{ GeV}) \Phi_i \Phi_j \Phi_k,
\] (19)
from which decay width of heavier flavon to lighter flavons is given by
\[
\Gamma(\Phi_i \to \Phi_j \Phi_k) \sim 10^{12} \text{ sec}^{-1}.
\] (20)
With this interactions, all heavier flavons decay into $\mathcal{LF}$ finally. If $\mathcal{LF}$ is heavier than sneutrinos, the following operators coming from Eq.(10) may contribute to $\mathcal{LF}$ decay:

$$\mathcal{L}_{\Phi NN} \sim m_{\text{SUSY}} \Phi_{\text{NN}}.$$  \hspace{1cm} (21)$$

Where $N$ is sneutrino. If $\mathcal{LF}$ is heavier than scalar g-quarks, the following operators coming from Eq.(5) may contribute too:

$$V \frac{M}{M_P^2} \phi_{\text{gqq}},$$

where $g$ is scalar g-quark and $q$ is doublet quark. The contributions from these operators are the same order as the contribution from Eq.(11). Hereafter, we assume $\mathcal{LF}$ is lighter than those scalar particles and g-quarks. In this case, $\mathcal{LF}$ decay channels to these particles are kinematically closed.

4 Estimation of RHN Mass Scale

At high temperature $T \gg m_{\text{SUSY}}$, dominant contribution to $\chi \chi \rightarrow \Phi \Phi$ come from U(1)$_Z$ gauge interaction, where $\chi$ is the particle in thermal bath. This interaction is in thermal equilibrium when

$$\Gamma(\chi \chi \rightarrow \Phi \Phi) \sim \frac{T^5}{V} > H \sim \frac{T^2}{m_P}$$

is satisfied. Note that $M_P = 2.43 \times 10^{18}$ GeV is reduced Planck mass and $m_P = 1.22 \times 10^{19}$ GeV is Planck mass. Evading overproduction of gravitino, $T < 10^7$ GeV must be satisfied with [12]. Then the constraint Eq.(23) leads following condition:

$$10^{10} \text{GeV} > V.$$  \hspace{1cm} (24)$$

However it is difficult to satisfy this condition in our model. Moreover, if flavon is in thermal equilibrium, there is a problem of over-production of flavon because U(1)$_Z$ gauge interaction is too weak at low temperature to cause appropriate pair annihilation of flavons. Based on this discussion, we assume U(1)$_Z$ gauge interaction is never in thermal equilibrium and the universe starts with low flavon number density $n_{\Phi}(T_{RH}) = 0$.

The interaction between U(1)$_Z$ gauge boson $A_{\mu}$ and chiral multiplet $(\psi, \Psi)$, where $\psi$ is fermion and $\Psi$ is boson, is given by

$$\mathcal{L}_{\text{gauge}} = ig_z A_{\mu} \sum_i z_i \left[ \bar{\psi}_{i,L} \gamma_{\mu} \psi_{i,L} + \bar{\Psi}_i \partial_{\mu} \Psi_i - \bar{\Psi}_i \partial_{\mu} \Psi_i \right],$$

from which thermally averaged cross sections are given by

$$\sum_\psi \langle \sigma_{\psi \psi \rightarrow \phi \phi} | v | \rangle n_{\phi}^2 = 55.1 C T^8,$$  \hspace{1cm} (26)$$

$$\sum_\psi \langle \sigma_{\phi \psi \rightarrow \phi \phi} | v | \rangle n_{\phi}^2 = 96.1 C T^8,$$  \hspace{1cm} (27)$$

$$\sum_\psi \langle \sigma_{\psi \psi \rightarrow \Phi \Phi} | v | \rangle n_{\phi}^2 = 96.1 C T^8,$$  \hspace{1cm} (28)$$

$$\sum_\psi \langle \sigma_{\phi \phi \rightarrow \Phi \Phi} | v | \rangle n_{\phi}^2 = 248.8 C T^8,$$  \hspace{1cm} (29)$$

$$C = \frac{21}{(2\pi)^5} \left( \frac{g_z z_{\phi}}{M_g} \right)^2,$$  \hspace{1cm} (30)$$

$$M_g = 2 g_z z_{\phi} V = 16 g_z V,$$  \hspace{1cm} (31)$$

where $\sum_\psi, \Psi$ does not contain flavon $\Phi$ and its fermion partner $\phi$ because $n_{\phi}$ and $n_{\psi}$ are negligible. Here we define the $\mathcal{LF}$ production rate $N_{LF}$ which means how many $\mathcal{LF}$s are generated per one degree of freedom of flavon and its fermion partner. Because the total degrees of freedom is 20, $N_{LF}$ is bounded from below.
by $1/20$ \(^2\). If we require that the masses of flavons and those fermion partners are smaller than 9 TeV, \(N_{LF}\) is bounded from above by 9 TeV/\(m_{LF}\) = 3. Therefore allowed range of \(N_{LF}\) is given by

\[
3 \geq N_{LF} \geq 0.05. \tag{32}
\]

The model dependence of flavon sector affects this analysis only through \(\epsilon\) and \(N_{LF}\). Using \(N_{LF}\), the Boltzmann equation for the LF number density \(n_{LF}\):

\[
n_{LF} = 5N_{LF}(n_{\phi} + n_{\Phi}), \tag{33}
\]

is given by

\[
\dot{n}_{LF} + 3Hn_{LF} = 2480N_{LF}CT^8, \tag{34}
\]

where Hubble constant \(H\) is given by

\[
H = 1.66\sqrt{g_\ast}\frac{T^2}{m_P}, \tag{35}
\]

\[
g_\ast = 341.25. \tag{36}
\]

Solving Eq.(34) with boundary condition \(n_{LF}(T_{RH}) = 0\), LF to entropy ratio is calculated as follow:

\[
\left(\frac{n_{LF}}{s}\right)_0 = \frac{15 \times 2480 \times 21m_PN_{LF}}{2\pi^2g_\ast \times 30.67(2\pi)^5} \left(\frac{g_\ast^2\zeta_{\phi}}{M_g^2}\right)^2 T_{RH}^3. \tag{37}
\]

Note that Eq.(37) does not depend on the definition of \(U(1)_Z\) gauge coupling constant \(g_z\) and charge normalization. Finally we require the density parameter

\[
\Omega_{LF} = \frac{m_{LF}n_{LF}}{\rho_c} \tag{38}
\]

satisfies Eq.(17) then we get

\[
\frac{V}{10^{12} \text{ GeV}} = (\epsilon^2 N_{LF})^{\frac{1}{2}} \left(\frac{T_{RH}}{10^5 \text{ GeV}}\right)^{\frac{3}{4}}, \tag{39}
\]

where

\[
s_0 = 2890/\text{cm}^3, \tag{40}
\]

\[
\rho_c = 1.05 \times 10^4 h^2 \text{ eV/cm}^3, \tag{41}
\]

are used [11].

If we assume

\[
10^7 \text{ GeV} \geq T_{RH} \geq 10^4 \text{ GeV} \gg m_{LF}, \tag{42}
\]

and the model dependent parameters as Eq.(32) and

\[
1 \geq \epsilon \geq 0.1, \tag{43}
\]

we get the allowed range of \(V\) as follow:

\[
12 \geq \frac{V}{10^{12} \text{ GeV}} \geq 0.09. \tag{44}
\]

This prediction is consistent with our previous result \(V \sim 10^{12} \text{ GeV}\) which comes from phenomenological constraints for proton life time and g-quark life time [7]. If we use \(V = 10^{12} \text{ GeV}\), reheating temperature is predicted as

\[
T_{RH} = (0.7 - 5.8) \times 10^5 \text{ GeV}. \tag{45}
\]

\(^2\)Note that 4 of 24 = 4 \times 6 are super-heavy or eaten by gauge boson, where 6 is total number of flavon superfields (\(\Phi, \Phi^c\)).
Finally we give some comments. In the case that $\mathcal{LF}$ is dominant component of dark matter as $\Omega_{LF} \sim \Omega_{DM}$, which is realized by putting $\epsilon(10^{12} \text{ GeV}/V) \sim 2 \times 10^{-4}$, $\epsilon$ is bounded from above by

$$\epsilon < 1.2 \times 10^{-4}.$$  

(46)

However, it seems difficult to explain such a small mixing angle.

If the final states of $\mathcal{LF}$ decay contain quarks, anti-proton flux may be significantly induced, which conflicts with cosmic-ray observations [13]. This problem is avoided when $\mathcal{LF}$ decay mainly into charged Higgs which does not couple to quarks. Such a type of model [14] can be constructed with $S_4$ flavor symmetry. For example, if all quarks are assigned to $S_4$-singlets and $SU(2)_W$ Higgs doublets $H^U$ and $H^D$ are assigned to one $S_4$-doublet and one $S_4$-singlet respectively, Yukawa interactions between $S_4$-doublet Higgs and quarks are forbidden. This assignment also solves Higgs-FCNC problem, as pointed in ref. [15]. However, as there is no room for model building in weak interaction, we can not suppress anti-proton production by weak interaction such as $\Phi \rightarrow \nu W^- e^+ \rightarrow \bar{p}$. It is not obvious whether the effects of weak interaction spoil this solution or not, which is left for future work.

5 Summary

In this paper, we have considered cosmic-ray anomaly observed by PAMELA based on $S_4$ flavor symmetric extra U(1) model. Identifying the particle decaying into positron as the lightest flavon which is the subdominant component of dark matter, reheating temperature of the universe and the mass scale of right handed neutrinos were related, and we estimated the mass scale of right handed neutrinos from the relation. As a result, the constraint that reheating temperature is low enough to suppress gravitino production gives vacuum expectation value of flavon around $10^{12}$ GeV, which is consistent with the prediction of our model. This result supports the idea of neutrino seesaw mechanism based on heavy right handed neutrino with $O(10^{12})$ GeV mass. Finally, monochromatic diffuse neutrino flux is expected at $E_{\nu} = m_\Phi/2$ in cosmic-ray as a prediction of the model.

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