Chapter 33

Indirect and Direct Detection of Dark Matter and Flavor Symmetry

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Abstract

Indirect and direct detection of Dark Matter is discussed in the D_6 flavor symmetric model. Dark Matter in this model is the D_6 singlet right handed neutrino n_S. The D_6 flavor symmetry predicts a certain mixings of leptons and also plays an important role in determining the final states of the Dark Matter annihilation. A large annihilation cross section, which is required to explain the positron excess in cosmic ray observed by PAMELA experiment is obtained by the Breit-Wigner enhancement mechanism. Moreover, a certain elastic cross section with nucleon is derived by the mixing of Higgses which intermediate in the elastic scattering $n_S q \to n_S q$.

33.1. Introduction

Many experimental evidences for the existence of Dark Matter (DM) are observed: for instance, rotation curves of spiral galaxy, CMB observation by WMAP, gravitational lensing and large scale structure of the Universe. DM candidate is often included as a stable particle due to a Z_2 symmetry in a particle physics model. A eligible DM has the thermally averaged annihilation cross section of $\langle \sigma v \rangle \sim 10^{-9}\ \mathrm{GeV}^{-2}$ in order to obtain the correct DM relic density.

Several years ago, PAMELA reported excess of positron fraction in the cosmic ray [2]. This observation can be explained by annihilation and/or decay of DM particles with mass of $\mathcal{O}(10^{2-3})\ \mathrm{GeV}$. In this case, the required annihilation cross section is $\mathcal{O}(10^{-7})\ \mathrm{GeV}^{-2}$ which is much larger than that for the relic DM density. Several ideas to overcome it are proposed such as the Sommerfeld enhancement, the Breit-Wigner enhancement [3][4], non-thermal DM production and decaying DM. The PAMELA experiment searches antiproton as well in the cosmic ray, and it is consistent with the background [5]. Therefore, if these signals are from annihilation and/or decay processes of DM particles, this implies that the leptophilic DM is preferable. However,

This talk is based on ref. [1].

	L_S	n_S	e^c_S	L_I	n_I	e^c_I
$SU(2)_L \times U(1)_Y$	$(\mathbf{2}, -1/2)$	$(\mathbf{1}, 0)$	$(\mathbf{1}, 1)$	$(\mathbf{2}, -1/2)$	$(\mathbf{1}, 0)$	$(\mathbf{1}, 1)$
D_6	$\mathbf{1}$	$\mathbf{1}'''$	$\mathbf{1}$	$\mathbf{2}'$	$\mathbf{2}'$	$\mathbf{2}'$
$\hat{Z}_2$	$+$	$+$	$-$	$+$	$+$	$-$
Z_2	$+$	$-$	$+$	$+$	$-$	$+$

Table 33.1
The $D_6 \times \hat{Z}_2 \times Z_2$ assignment for the leptons. $L_{I,S}$ stands for the $SU(2)_L$ doublet leptons, and $e^c_{I,S}$ and $n_{I,S}$ are the $SU(2)_L$ singlet leptons.

	ϕ_S	ϕ_I	η_S	η_I	φ
$SU(2)_L \times U(1)_Y$	$(\mathbf{2}, -1/2)$	$(\mathbf{2}, -1/2)$	$(\mathbf{2}, -1/2)$	$(\mathbf{2}, -1/2)$	$(\mathbf{1}, 0)$
D_6	$\mathbf{1}$	$\mathbf{2}'$	$\mathbf{1}'''$	$\mathbf{2}'$	$\mathbf{1}$
$\hat{Z}_2$	$+$	$-$	$+$	$+$	$+$
Z_2	$+$	$+$	$-$	$-$	$+$

Table 33.2
The $D_6 \times \hat{Z}_2 \times Z_2$ assignment for the Higgs bosons.

even if the DM is leptophilic, the resultant positron fraction depends on the flavor of final state leptons. For instance, if the final state of annihilation and/or decay of the DM is $\tau^+\tau^-$, it will overproduce gamma-rays as final state radiation [6][7]. Therefore it is important to determine the flavor of final state leptons theoretically, and it could be possible by flavor symmetry of elementary particles which predicts the mixing of leptons.

In this talk, we discuss the explanation of the positron excess in the cosmic ray observed by PAMELA in the model based on the D_6 flavor symmetry. The final states of the annihilation of DM are controlled by the D_6 flavor symmetry. The large annihilation cross section is obtained by the Breit-Wigner enhancement. The elastic cross section for the direct detection of DM is also discussed briefly, and is obtained through the mixing of Higgses. The predicted elastic cross section is compared with the XENON100 and CDMS II results.

33.2. The Model

We extend the SM by introducing three generations of right-handed neutrino $n_{S,I}$, Higgs doublets $\phi_{I,S}$, inert doublets $\eta_{I,S}$ which have no vacuum expectation values (VEVs), and one generation of inert singlet φ where $I = 1, 2$ and S denote D_6 doublet and singlet, respectively. We also impose the additional discrete family symmery $\hat{Z}_2 \times Z_2$ in order to suppress FCNC of the quark sector and forbid Dirac neutrino masses. In addition the imposed Z_2 symmetry stabilize a DM candidate. The $D_6 \times \hat{Z}_2 \times Z_2$ assignment is shown in Tab.33.1 and 33.2. The invariant Lagrangian of the right handed neutrino sector under the imposed symmetry $D_6 \times \hat{Z}_2 \times Z_2$ is written as

$$\begin{aligned} \mathcal{L}_Y &= \sum_{a,b,d=1,2,S} \left[Y^{ed}_{ab} L_a \phi_d e^c_b + Y^{\nu d}_{ab} \eta^\dagger_d L_a n_b \right] \\ &+ \sum_{I=1,2} \frac{M_1}{2} n_I n_I - \frac{M_S}{2} n_S n_S - \sum_{I=1,2} \frac{\mathfrak{S}_1}{2} \varphi n_I n_I - \frac{\mathfrak{S}_S}{2} \varphi n_S n_S + \mathrm{h.c} \end{aligned} \quad (33.1)$$

where the couplings $\mathfrak{S}_1$ and $\mathfrak{S}_S$ are complex in general. The following MNS (Maki-Nakagawa-Sakata) matrix is derived at leading order by the D_6 flavor symmetry.

$$V_{MNS} \simeq \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\frac{1}{\sqrt{2}}\sin\theta_{12} & \frac{1}{\sqrt{2}}\cos\theta_{12} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}}\sin\theta_{12} & \frac{1}{\sqrt{2}}\cos\theta_{12} & \frac{1}{\sqrt{2}} \end{pmatrix}. \tag{33.2}$$

The D_6 flavor symmetry gives two predictions. One is that the maximal mixing of atmospheric neutrino is derived. The other one is that inverted hierachy for the neutrino masses is only allowed [8].

33.3. DM Relic Density and $\mu \to e\gamma$ Constraint

Several DM candidates which are Z_2 odd particles are included in the model. We assume that DM candidate is the D_6 singlet right handed neutrino n_S. The assumption is interesting since the Yukawa couplings are constrained by the D_6 symmetry and a few parameters which are relative with DM physics only remain in the model. We investigate whether the correct DM relic density can be satisfied by the DM n_S. Due to the D_6 flavor symmetry, the neutrino Yukawa couplings $\eta_S^\dagger \overline{\ell_i} Y_{ij}^\nu n_j$ are restricted as

$$Y_{ab}^\nu \simeq \begin{pmatrix} 0 & 0 & h \\ 0 & 0 & \frac{m_e}{m_\mu}h \\ 0 & 0 & 0 \end{pmatrix} \qquad \text{for charged leptons,} \tag{33.3}$$

$$Y_{ab}^\nu \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & h \end{pmatrix} \qquad \text{for neutrinos,} \tag{33.4}$$

where m_e, m_μ are electron and muon mass and h the Yukawa coupling of $\mathcal{O}(1)$. One can see that $e^\pm$ are dominantly generated as charged leptons due to the D_6 flavor symmetry. This point is crucial in order to explain the positron excess in the cosmic ray observed by PAMELA. The thermally averaged annihilation cross section of DM is calculated as

$$\langle \sigma_1 v \rangle \simeq \frac{|h|^4}{4\pi} \frac{M_S^2(M_S^4 + M_\eta^4)}{(M_S^2 + M_\eta^2)^2} \frac{T}{M_S}. \tag{33.5}$$

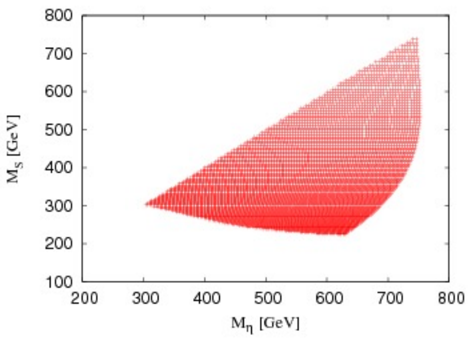
where M_η is η mass which is included in the scalar potential $\mathcal{V}(\phi, \eta, \varphi)$ and T is the temperature of the Universe.

We also must take into account the constraint from Lepton Flavor Violation. In particular, $\mu \to e\gamma$ gives a severe constraint. We explore allowed parameter region from the DM relic density, Lepton Flavor Violation, the perturbativity of the model $|h| < 1.5$ and the condition of DM $M_S < M_\eta$. The left hand side of Fig. 33.1 shows the allowed parameter region from these constraints. One can find that the allowed mass region of M_S is $230\ \text{GeV} \lesssim M_S \lesssim 750\ \text{GeV}$ from the figure.

33.4. Indirect Detection of DM

The positron excess in the cosmic ray is explained by the annihilation channel $n_S n_S \to \varphi \to e^+e^-$. This process is s-channel and enhanced by the Breit-Wigner enhancement mechanism when the relation $2M_S \simeq M_R$ is satisfied where M_R is the resonance particle mass. A similar analysis is done in ref. [9]. The resonance particle R is a mass eigenstate of Higgses and expressed by using the mixing matrix $\mathcal{O}$ as follows

$$R = \mathcal{O}_I \phi_I + \mathcal{O}_S \phi_S + \mathcal{O}_\varphi \varphi. \tag{33.6}$$



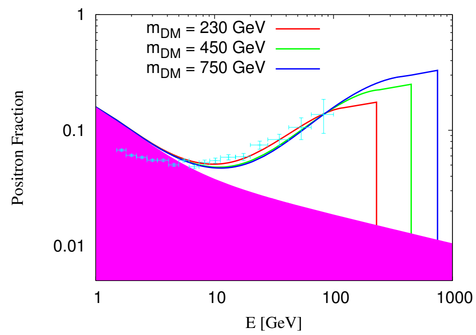


Figure 33.1. The allowed parameter region from the thermal DM relic density and $\mu \to e\gamma$ in the (M_η-M_S) plane (the left figure). The comparison of the positron flux with the PAMELA result for $M_S = 230, 450, 750$ GeV (the right figure). The annihilation cross section $\langle \sigma_2 v \rangle$ is taken as 8.5×10^{-8}, 2.6×10^{-7} and 6.8×10^{-7} GeV^{-2} respectively.

If the condition $\gamma_R/\Delta \ll 1$ is satisfied, the annihilation cross section through the s-channel is calculated as

$$\langle \sigma_2 v \rangle \simeq \frac{\sqrt{\pi}}{10(4\pi)^4} |h|^4 \mathcal{O}_\varphi^2 \left(\mathrm{Re}\mathfrak{S}_S\right)^2 \frac{m_e^2}{M_\eta^4} \left(\frac{M_S}{T}\right)^{3/2} e^{-\Delta M_S/T} \tag{33.7}$$

where the dimensionless parameter γ_R is defined as $\gamma_R \equiv \Gamma_R/M_R$ and the mass degeneracy Δ is $\Delta \equiv 1 - 4M_S^2/M_R^2$ [10][11]. The annihilation cross section $\langle \sigma_2 v \rangle$ severely changes by the relative velocity of DM v. Namely, This enhancement is only effective at the present universe, and neglected at the early universe. As a result, the size discrepancy of the annihilation cross section between obtaining the correct DM relic density and explaining the positron excess is solved. The positron flux is calculated by solving the diffusion equation [12]. The flux calculated in the model is shown in the right hand side of Fig.33.1 where Isothermal profile is assumed here as DM density profile. The contours of the boost factor which is defined as $BF \equiv \langle \sigma v \rangle / 3.0 \times 10^{-9}$ here is shown in Fig.33.2 for $\sqrt{\Delta} = 10^{-6}$ and 10^{-7}. The red region stands for $\gamma_R/\Delta \ll 1$ region. The analysis is valid for only in the red region. From the figure, one can see that the relation $\mathrm{Re}\mathfrak{S}_S \ll \mathrm{Im}\mathfrak{S}_S$ and $\sqrt{\Delta} \lesssim 10^{-6}$ must be satisfied in order to obtain a large boost factor BF. We must take into account the constraint from no excess of anti-proton flux. Due to the constraint, $\langle \sigma_3 v \rangle / \langle \sigma_2 v \rangle \lesssim 10^{-2}$ is required where $\langle \sigma_3 v \rangle$ is the annihilation cross section of $n_S n_S \to q\bar{q}$. This constraint corresponds to $|\mathcal{O}_S|/|\mathfrak{S}_S| \lesssim 10^{-12}$, and it is the very severe constraint.

33.5. Direct Detection of DM

The elastic cross section with nucleon is derived from the mixing of Higgses. In particular, the mixing φ-ϕ_S is important since ϕ_S only couples to quarks. The SM Higgs is a superposition of Higgses ϕ_I, ϕ_S and φ,

$$\text{SM-higgs} = \mathcal{U}_I \phi_I + \mathcal{U}_S \phi_S + \mathcal{U}_\varphi \varphi. \tag{33.8}$$

The elastic cross section is proportional to the mixing $\sigma_{\mathrm{SI}}^N \propto |\mathcal{U}_S \mathcal{U}_\varphi \mathfrak{S}_S Y^q|^2$ We compare the predicted elastic cross section with direct detection experiments such as XENON100 and CDMS II which give the most severe constraint on direct detection of DM. As a result, we obtain the predicted elastic cross section which can be verified by the next future direct detection experiment XENON1T for $\mathcal{U}_S \mathcal{U}_\varphi \mathfrak{S}_S \simeq 0.1$.

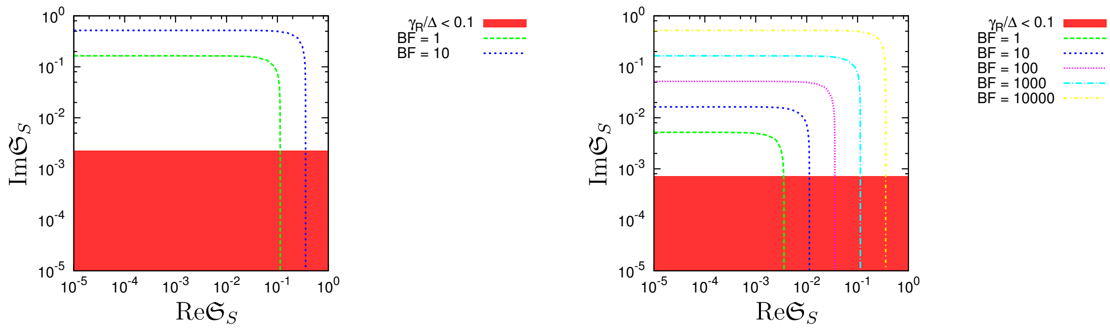


Figure 33.2. The contours of the boost facotor BF defined in the text. γ_R is defined as $\gamma_R = \Gamma_R/M_R$ where Γ_R is the decay width of the resonance particle R.

33.6. Summary

Indirect and direct detection of DM have been discussed in D_6 flavor symmetric model. The D_6 flavor symmetry gives the predictions for the mixings of leptons. The mass of DM n_S is constrained to $230 \lesssim M_S \lesssim 750$ GeV by the thermal DM relic density and Lepton Flavor Violation. The $e^\pm$ excess in the cosmic ray is explained by the Breit-Wigner enhancement. The flavor of the final states of the DM annihilation is determined by the D_6 flavor symmetry and the flavor is almost $e^\pm$.

The elastic scattering between DM and quarks occurs through the Higgs mixing. A certain parameter region of the Higgs mixing will be verified by the next future direct detection experiments such as XENON1T.

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