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Gamma rays from dark matter annihilation in three-loop radiative neutrino mass generation models

Talal Ahmed Chowdhury [a,b], Salah Nasri [c,b,*]

[a] Department of Physics, University of Dhaka, P.O. Box 1000, Dhaka, Bangladesh
[b] The Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, I-34014, Trieste, Italy
[c] Department of Physics, UAE University, P.O. Box 17551, Al-Ain, United Arab Emirates

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A B S T R A C T

We present the Sommerfeld enhanced Dark Matter (DM) annihilation into gamma ray for a class of three-loop radiative neutrino mass models with large electroweak multiplets where the DM mass is in O(TeV) range. We show that in this model, the DM annihilation rate becomes more prominent for larger multiplets and it is already within the reach of currently operating Imaging Atmospheric Cherenkov telescopes (IACTs), High Energy Stereoscopic System (H.E.S.S.). Furthermore, Cherenkov Telescope Array (CTA), which will begin operating in 2030, will improve this sensitivity by a factor of $\mathcal{O}(10)$ and may exclude a large portion of parameter space of this radiative neutrino mass model with larger electroweak multiplet. This implies that the only viable option is the model with lowest electroweak multiplets i.e. singlets of $SU(2)_L$ where the DM annihilation rate is not Sommerfeld enhanced and hence it is not yet constrained by the indirect detection limits from H.E.S.S. or future CTA.

1. Introduction

We are yet to identify the mass and particle nature of the Dark Matter (DM) of the universe despite having extensive astrophysical and cosmological observations supporting its existence. Recently the DM, having quantum numbers under the Standard Model (SM) gauge group $SU(2)_L \times U(1)_Y$ and with mass in the TeV range, has come under the focus of Imaging Atmospheric Cherenkov Telescopes (IACT) as gamma ray produced in the DM annihilation at the central region of the Milky Way galaxy is within the detection reach of IACTs [1–4].

The flux of the gamma ray photons from cosmic sources rapidly falls when their energies reach $E \gtrsim$ O(TeV). For this reason, the satellite which has the detection area of sub-m^2, is not very sensitive for the very high energetic (VHE) gamma ray of the energy range, 100 GeV–100 TeV. On the other hand, such high energy gamma ray interacts with the upper region of the atmosphere and creates a shower of very energetic secondary charged particles which reaches at about 10 km height. These particles move faster than the speed of light in the air and therefore emit the faint blue Cherenkov light. This Cherenkov light is beamed around the direction of the incident primary photon and it illuminates the ground of about 50,000 m^2, which is often referred as Cherenkov light pool. Only 100 photons per m^2 on the ground can be seen for a primary photon of TeV energy. So if a telescope is somewhere within the light pool and has large mirror area to collect enough photons, it will observe the air shower. Therefore, the effective detection area of a Cherenkov telescope is approximately given by the area of the light pool which is much larger than that of a satellite. The prominent IACTs like MAGIC [5], VERITAS [6], CANGAROO [7] and H.E.S.S. [8] have revealed intriguing astrophysical VHE gamma ray sources of our universe. In [9,10] H.E.S.S. collaboration presented search result for gamma signal coming from DM annihilation in the inner region of Milky Way and put upper limits on the annihilation cross section $\langle\sigma v\rangle$ for the DM in the TeV mass range that is not within the reach of collider searches or direct detection experiments.

In addition, the non-relativistic (NR) DM which has O(TeV) mass and electroweak charge, receives the non-perturbative Sommerfeld enhancement [11–34] which increases the DM annihilation rate into gauge bosons, i.e. DM DM $\to WW, ZZ, \gamma\gamma, \gamma Z$, significantly. As a consequence, this class of NR DM with TeV mass range, has better prospects of being detected in currently operating H.E.S.S. or future CTA [35,36] which will begin operation in about 2030.

Apart from the DM nature of the universe, the origin and smallness of the neutrino mass is yet to be concluded. The Krauss–Nasri–Trodden (KNT) model [37] ties these two issues together by

* Corresponding author.
E-mail addresses: talal@du.ac.bd (T.A. Chowdhury), snasri@uaeu.ac.ae (S. Nasri).

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radiatively generating neutrino mass[1] at three-loop with DM particle running in the loop. The Beyond Standard Model (BSM) content of the model consists of two single charged singlet scalars, S_1^+, S_2^+ and three singlet RH neutrinos, N_{R_i}, $i = 1, 2, 3$ under SM gauge group with masses lie in the GeV–TeV range. Here, the lightest singlet RH neutrino N_{R_1} plays the role of DM. Subsequently, KNT model can be generalized [39] by replacing S_2^+ with $\mathbf{\Phi}$ having integer isospin and hypercharge, $Y = 1$ and N_{R_i} with $\mathbf{F}_i$ that has integer isospin and $Y = 0$ under SM gauge group. In the generalized KNT model, the lightest neutral fermion component, F_1^0 is the viable DM candidate. Such replacement in KNT model with large electroweak multiplets have been studied for triplet [40], 5-plet [41] and 7-plet [42] cases. In [43], we have investigated the charged lepton flavor violating processes in the generalized KNT model. In this work we focus on 5-plet and 7-plet cases because the Z_2 symmetry, $\{S_2^+, N_{R_i}\} \to \{-S_2^+, -N_{R_i}\}$ needed to prevent the Dirac neutrino mass term in the Lagrangian, is not required anymore for larger multiplets like in 5-plet and 7-plet cases.

The article is organized as follows. In section 2, we present the generalized KNT model. Section 3 describes the formalism to calculate Sommerfeld enhanced DM annihilation processes in generalized KNT model. In section 4, we present the relic densities of the DM candidate, including the correction due to SE, in 5-plet and 7-plet cases via thermal freeze-out process and also via non-thermal out-of-equilibrium decay. The DM annihilation cross sections into electroweak bosons at the galactic center are presented in section 5. Finally we conclude in section 6.

2. The model

Apart from the SM field content, we add the following BSM fields in the generalized KNT model which are charged under SM gauge group, $SU(3)_c \times SU(2)_L \times U(1)_Y$ as

$$\text{Complex scalars: } S_1^+ \sim (0,0,1),\ \mathbf{\Phi} \sim (0, j_\phi, 1),\ \text{and}$$
$$\text{Real fermions: } \mathbf{F}_{1,2,3} \sim (0, j_F, 0) \tag{1}$$

where j_ϕ and j_F are integer isospin of $SU(2)_L$.

In this comparative study, we focus on two set of models in this class; 5-plet model: $\mathbf{\Phi} \sim (0, 2, 1)$ & $\mathbf{F}_{1,2,3} \sim (0, 2, 0)$ and 7-plet model: $\mathbf{\Phi} \sim (0, 3, 1)$ & $\mathbf{F}_{1,2,3} \sim (0, 3, 0)$.

The SM Lagrangian is augmented in the following way,

$$\mathcal{L} \supset \mathcal{L}_{SM} + \{f_{\alpha\beta}\overline{L_\alpha^c}.L_\beta S_1^+ + g_{i\alpha}\overline{\mathbf{F}_i}.\mathbf{\Phi}.e_{\alpha_R} + h.c.\} - \frac{1}{2}\overline{\mathbf{F}_i^c}M_{F_{ij}}\mathbf{F}_j - V(H, \mathbf{\Phi}, S_1) + h.c., \tag{2}$$

where, c denotes the charge conjugation and dot sign, in shorthand, refers to appropriate $SU(2)$ contractions. Also L_α and e_{R_α} are the LH lepton doublet and RH charged leptons respectively and Greek alphabet α stands for generation index. Moreover, $[F]_{\alpha\beta} = f_{\alpha\beta}$ and $[G]_{i\alpha} = g_{i\alpha}$ are 3×3 complex antisymmetric and general complex matrices respectively. Finally, H denotes the SM Higgs doublet.

The scalar potential is given by,

$$V(H, \mathbf{\Phi}, S_1) = V(H) + V(\mathbf{\Phi}) + V(S_1) + V_1(H, \mathbf{\Phi}) + V_2(H, S_1) + V_3(\mathbf{\Phi}, S_1) \tag{3}$$

The three-loop neutrino mass generation and the DM stability depend on the V_3 term of Eq. (3). Explicitly the relevant terms of V_3 for 5-plet and 7-plet models are,

$$V_3^{(5)} \supset \frac{\lambda_S}{4}(S_1^-)^2\mathbf{\Phi}_{abcd}\mathbf{\Phi}_{efgh}\epsilon^{ae}\epsilon^{bf}\epsilon^{cg}\epsilon^{dh} + \lambda S_1^-\mathbf{\Phi}^{*abcd}\mathbf{\Phi}_{abef}\mathbf{\Phi}_{cdjl}\epsilon^{ej}\epsilon^{fl} + h.c \tag{4}$$

$$V_3^{(7)} \supset \frac{\lambda_S}{4}(S_1^-)^2\mathbf{\Phi}_{abcdef}\mathbf{\Phi}_{ghijkl}\epsilon^{ag}\epsilon^{bh}\epsilon^{ci}\epsilon^{dj}\epsilon^{ek}\epsilon^{fl} + h.c. \tag{5}$$

Here the λ term in Eq. (4) is not invariant under Z_2 and eventually induce the decay of F_1^0 where the width is $\Gamma_{\text{DM}} \sim \lambda^2$. But, as pointed out in [41], the bound on DM mean life-time sets λ to be very small, and in the limit when $\lambda \to 0$, the Z_2 symmetry emerges. On the other hand, the λ term is absent in Eq. (5) because $j_\phi \otimes j_\phi$ contains symmetric (antisymmetric) irreducible representation with same isospin T_ϕ for even (odd) integer isospin which is further contracted with $\mathbf{\Phi}^\dagger$ to obtain a singlet. So, for two identical scalar multiplets, the antisymmetric combination is zero and hence no λ term for $j_\phi = 3$.

As pointed out in [43], the mass splittings among component fields of the scalar multiplet is controlled by $\lambda_{H\phi 2}(\mathbf{\Phi}^\dagger.H).(H^\dagger.\mathbf{\Phi}) \subset V_2$ term after electroweak symmetry breaking and allowed splittings only lead to $\Delta m_{ij}^2/M_0^2 \sim 10^{-3}$ for invariant mass of the scalar multiplet, $M_0 = 10$ TeV and the ratio becomes smaller for $M_0 > 10$ TeV. On the other hand, the mass splittings in fermionic component fields are zero at tree-level and only receive $O(100)$ MeV splittings due to radiative correction after electroweak symmetry breaking. Therefore such scenario is can be considered as near-degenerate case.

3. Sommerfeld enhanced dark matter annihilation

3.1. DM candidate

In the generalized KNT model, the lightest neutral component of the fermion multiplet, F_1^0 is the viable DM candidate. In comparison, the neutral component of the scalar multiplet, $\phi^0 = \frac{1}{\sqrt{2}}(S + iA)$ could have provided S to be DM but it is ruled out as it induces Z-mediated dark matter nucleon scattering of the order $10^{-39}\,\text{cm}^2$ which is much larger than the exclusion limit set by the direct detection experiments [55]. One can avoid this DM-nucleon scattering channel if the splitting between S and A is large enough to make this scattering kinematically forbidden but there is no renormalizable term in the Lagrangian which can induce such splitting in a generic way. Still, higher dimensional operator can split the S and A component [45] but then it is needed to address the UV completion of the model. Therefore, we restrict ourselves only to the renormalizable Lagrangian, and therefore the DM candidate is set to F_1^0.

3.2. SE annihilation cross-sections

When the DM is non-relativistic, $v_{\text{DM}} \ll c$ and $m_{W,Z} \ll m_{\text{DM}}$, the exchange of massive W and Z gauge bosons between DM components will induce Yukawa potential and γ exchange will induce Coulomb potential which in turn significantly modifies the wavefunction of the incoming DM states and enhances the annihilation cross-sections. This phenomenon is known as Sommerfeld Enhancement (SE). The calculation of Sommerfeld enhanced DM annihilation cross section is well studied subject so here we follow the prescriptions given in [34,45]. In the following we briefly review them to set up our notation.

As the Sommerfeld enhancement is considered for $2 \to 2$ processes, we first define 2-particle states which consist of incoming component fields of fermion multiplet. Sommerfeld enhancement takes place in DM (co)annihilation processes with final states $W^\pm$, Z and γ bosons so we only consider the 2-particle states which

[1] For a review of radiative neutrino mass generation models, please see [38].