

keV Photon Emission from Light Nonthermal Dark Matter

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We propose a possible explanation for the recent claim of an excess at 3.5 keV in the X-ray spectrum within a minimal extension of the standard model that explains dark matter and baryon abundance of the universe. The dark matter mass in this model is $\mathcal{O}(\text{GeV})$ and its relic density has a non-thermal origin. The model includes two colored scalars of $\mathcal{O}(\text{TeV})$ mass ($X_{1,2}$), and two singlet fermions that are almost degenerate in mass with the proton ($N_{1,2}$). The heavier fermion N_2 undergoes radiative decay to the lighter one N_1 that is absolutely stable. Radiative decay with a life time $\sim 10^{23}$ seconds can account for the claimed 3.5 keV line, which requires couplings $\sim 10^{-3} - 10^{-1}$ between $X_{1,2}$, $N_{1,2}$ and the up-type quarks. The model also gives rise to potentially detectable monojet, dijet, and monotop signals at the LHC.

I. INTRODUCTION

Recently XMM-Newton observatory has found an excess at 3.5 keV X-ray in the spectrum of 73 galaxy clusters [1, 2]. If this excess persists such a photon emission can be the result of the late decay and/or annihilation of multi-keV mass dark matter, or decay of a metastable particle to daughter(s) with a keV mass splitting. Dark matter induced 3.5 keV photon excess has been recently studied in the scenario of extend neutrino sector [1, 3], the axion [4] or its supersymmetric partner axino [5], string moduli [6], and annihilation or decay via low energy effective operators [7]. In this paper, we investigate the possibility of the decay of a light nonthermal dark matter, as proposed in previous work [8], which connects the DM relic density to baryogenesis.

II. THE MODEL

The model is a minimal extension of the SM that includes iso-singlet color-triplet scalars X_α and SM singlet fermions N_a . The Lagrangian includes only renormalizable interactions and is given by

$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{new}} \\ \mathcal{L}_{\text{new}} &= (\lambda_{\alpha ai} X_\alpha^* N_a u_i^c + \lambda'_{\alpha ij} X_\alpha d_i^c d_j^c + \frac{1}{2} M_a N_a N_a + \text{h.c.}) \\ &+ m_\alpha^2 |X_\alpha|^2 + (\text{kinetic terms}). \end{aligned} \quad (1)$$

Here $1 \leq i, j \leq 3$ denote flavor indices (color indices are omitted for simplicity), and α and a denote the number of X and N fields respectively.

The model with two copies of X ($\alpha = 1, 2$) and one copy of N ($a = 1$) can give rise to baryogenesis and a viable DM candidate [8]. This is the minimum requirement for generation of baryon asymmetry from the interference of tree-level and one-loop diagrams in $X_{1,2}$ decay. Moreover, the N field can be the DM if its mass lies within the range $m_p - m_e \leq M_1 \leq m_p + m_e$ (m_p and m_e being the

proton mass and the electron mass respectively). The conditions $M_1 \leq m_p + m_e$ and $m_p - m_e \leq M_1$ ensure that the decay channels $N \rightarrow p + e^- + \bar{\nu}_e$, $\bar{p} + e^+ + \nu_e$ and $p \rightarrow N + e^+ + \nu_e$ are kinematically forbidden. The former implies stability of N , while the latter prevents catastrophic proton decay. Therefore, together they yield a suitable DM candidate whose stability is tied to that of the proton.

As discussed in [8], obtaining the correct DM abundance in this model requires a non-thermal mechanism. This is because N interactions with the up-type quarks bring it into thermal equilibrium with the plasma at temperatures as low as $T \sim M_1 \approx \mathcal{O}(\text{GeV})$. However, for $m_{1,2} \gtrsim (\text{TeV})$, to be compatible with the LHC bounds, thermal freeze-out results in overabundance of N according to the Lee-Weinberg bound [9]. Late decay of a scalar field that reheats the universe to sub-GeV temperatures provides a suitable non-thermal alternative for producing the correct DM relic abundance. The late decay produces $X_{1,2}$ whose subsequent decay creates DM particles and generates baryon asymmetry of the universe.

Such a common non-thermal origin for DM and baryogenesis, when combined with fact that N is a viable DM candidate only if $M_1 \approx \mathcal{O}(\text{GeV})$, can provide a natural explanation of the baryon-DM coincidence puzzle [10] (for a detailed discussion, see [8]).

III. 3.5 KEV PHOTON FOR LATE DECAY

Now consider the case with two copies of N ($a = 1, 2$) with $m_p - m_e \leq M_{1,2} \leq m_p + m_e$. In this case, then lighter singlet (which we call N_1) will be absolutely stable. The other field N_2 , which is heavier, is unstable but can have a very long life time. If N_2 is stable on cosmological time scales, then both N_1 and N_2 contribute to the DM relic abundance. As mentioned above, N_1 and N_2 are produced from the decay of $X_{1,2}$. Hence, for $\lambda_1 \sim \lambda_2$, they have comparable abundances and make similar contributions to the DM relic density.

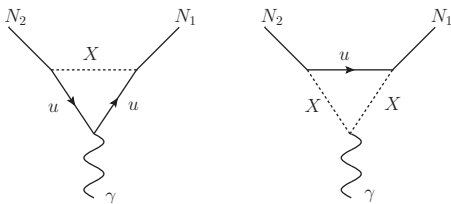


FIG. 1: Feynman diagrams for the $N_2 \rightarrow N_1 \gamma$ decay.

We note that $\Delta M \equiv M_2 - M_1 \leq 2m_e$. Therefore, since both N_1 and N_2 are electrically neutral, the only decay mode that is allowed is $N_2 \rightarrow N_1 + \gamma$. The relevant diagrams for this decay are shown in Fig. 1. For an on-shell photon, gauge-invariance implies that only interactions terms of the form $\bar{\psi}_1 \sigma^{\mu\nu} F_{\mu\nu} \psi_2$ make a non-zero contribution to the decay process [11]. Here $\psi_{1,2}$ are Majorana fermions that are made of Weyl fermions $N_{1,2}$.

The resulting decay width is given by

$$\Gamma_{N_2} \simeq 2^2 \times \frac{|\lambda_1 \lambda_2|^2}{64\pi^4} \alpha_{\text{em}} \Delta M^3 \frac{M_N^2}{m_X^4}. \quad (2)$$

Here we have assumed that N_1 , N_2 and X_1 , X_2 have similar masses that are denoted M_N and m_X respectively. Also, for simplicity, we have assumed that X_1 and X_2 have the same couplings, λ_1 and λ_2 respectively, to all flavors of u^c . With this assumptions, the factor of 2^2 on the right-hand side of (2) accounts for the interference of diagrams with X_1 and X_2 in the loop.

It is worth noticing that the decay width depends on the relative phase of N_1 and N_2 masses. As a result, a much narrower decay width can be achieved if M_1 and M_2 have opposite phases:

$$\Gamma_{N_2} \simeq 2^2 \times \frac{|\lambda_1 \lambda_2|^2}{64\pi^4} \alpha_{\text{em}} \frac{\Delta M^5}{m_X^4}. \quad (3)$$

To match the observed X-ray flux, the life time of N_2 should follow the estimate $\tau_{N_2} \approx 10^{29} \text{ s} \cdot (\text{keV}/M_N)$ according to Ref. [2]. The life time is inversely proportional to the DM mass for a given abundance in the host galaxy. Note that this estimate is subject to astrophysical uncertainties. For $M_N \approx \mathcal{O}(\text{GeV})$, we find $\Gamma_{N_2} = 0.7 \times 10^{-47} \text{ GeV}$. Considering $m_X \approx 2 \text{ TeV}$ (to be within the LHC reach) and $\Delta M = 3.5 \text{ keV}$, we require $|\lambda_1 \lambda_2| = 0.7 \times 10^{-6}$ for the generic case in Eq. 2 and $|\lambda_1 \lambda_2| = 0.2$ for the special case in Eq. 3, in order to account for the emission of 3.5 keV X-ray photon. Such values of λ can give rise to successful baryogenesis (see [8]) as well as potential signals at the LHC (which we discuss in the next section).

IV. OTHER SIGNALS OF THE MODEL

Radiative decay $N_2 \rightarrow N_1 + \gamma$ is the most significant (and perhaps the only detectable) signal of the model in direct and indirect detection experiments. This decay

can in principle produce a photon line with energy up to $2m_e$, corresponding to the maximum value of ΔM allowed by stability of DM candidate and proton. In this case, however, we need much smaller coupling strengths than those mentioned in the previous section in order to have any observable signal at the present time.

Since N only couples to a particular chirality of up-type quarks, spin-independent interactions that arise from effective operators of the form $(\bar{\psi}_N \psi_N)(\bar{\psi}_q \psi_q)/m_X^2$ between the DM and quarks are suppressed $\propto M_N^2/m_X^2$ (ψ_N and ψ_q are four-component fermions representing N and quark fields respectively). There are other spin-independent interactions with nucleons that arise from twist-2 quark operators and one-loop diagrams that couple N to gluons [12]. The corresponding elastic scattering cross section for all of these interactions is suppressed $\propto m_X^{-8}$, which gives rise to $\sigma_{\text{SI}} \lesssim 10^{-16} - 10^{-15} \text{ pb}$ for $m_X \sim \mathcal{O}(\text{TeV})$. This is considerably below the reach of upcoming experiments, and the neutrino background for DM mass of $\mathcal{O}(\text{GeV})$.

The spin-dependent cross-section is only suppressed $\propto m_X^{-4}$ as one has effective interactions of the form $(\bar{\psi}_N \gamma_5 \gamma^\mu \psi_N)(\bar{\psi}_q \gamma_5 \gamma_\mu \psi_q)/m_X^2$. This results in $\sigma_{\text{SD}} \lesssim 10^{-6} - 10^{-5} \text{ pb}$, for $m_X \sim \mathcal{O}(\text{TeV})$, which is much below the bounds from current experiments [13], as well as the upcoming detection experiments. It is also significantly below the current LHC bounds on σ_{SD} [14], but in the vicinity of the LHC future reach [15].

Indirect detection signals from DM annihilation will be negligible in this model. The DM annihilation rate is $\langle \sigma_{\text{ann}} v \rangle \sim \lambda^4 |\vec{p}|^2 / m_X^4$, where \vec{p} is the three-momentum of annihilating DM particles. For $m_X \sim \mathcal{O}(\text{TeV})$ and $\lambda \leq \mathcal{O}(1)$, we have $\langle \sigma_{\text{ann}} v \rangle \ll 10^{-31} \text{ cm}^3 \text{ s}^{-1}$, which is well below the current limits from DM annihilation to photons set by the Fermi-LAT [16]. The neutrino signal from annihilation of DM particles captured inside the Sun, which depends on σ_{SD} , is also negligible due to its low capture rate, evaporation at $M_N \sim \mathcal{O}(\text{GeV})$ as well as incapability to annihilate into heavy mesons that can decay before being absorbed by solar medium.

DM interactions with matter have a novel signature in this model that may be seen. The effective interaction $Nu^c d^c d^c$ leads to baryon destroying inelastic scattering of N off nucleons, similar to the model in [17], which may have an appreciable rate for nucleon decay experiments.

Moreover, for $\lambda_1, \lambda_2 \lesssim 0.1$ this model can be probed at the LHC through its distinctive monojet signatures via a resonant s -channel exchange of X . If $\lambda_1, \lambda_2 \sim 10^{-3}$, the two jet + missing transverse energy (\cancel{E}_T) channel can be searched for instead. The LHC search strategies have been studied in Ref. [18]. The coupling size required by the X-ray excess is below the current experimental constraint but can be confronted with future LHC data. If the λ coupling to the top quark is significant, a monotop or ditop + \cancel{E}_T can also emerge.

V. CONCLUSION

In conclusion, we have shown that it is possible to explain the recent claim of an excess at 3.5 keV in the X-ray spectrum within a minimal extension of the SM that explains DM and baryon abundance of the universe from a non-thermal origin. The minimum field content that is required includes two colored scalars $X_{1,2}$ and two singlet fermions $N_{1,2}$. The $N_{1,2}$ fermions are almost degenerate in mass with the proton and are coupled to the up-type quarks through interaction terms $\lambda X^* N u^c$. The lighter singlet N_1 is absolutely stable, while the heavier one N_2 undergoes radiative decay $N_2 \rightarrow N_1 + \gamma$ with a long life-

time $\sim 10^{23}$ seconds. This decay produces the claimed 3.5 keV photon line for $m_X \sim \mathcal{O}(\text{TeV})$ and $\lambda \sim 10^{-3}$ - 10^{-1} . The model can also be probed through monojet, dijet, and monotop signals at the LHC.

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