Physics Letters B 738 (2014) 118–122

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Magnetic dark matter for the X-ray line at 3.55 keV

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ARTICLE INFO

Article history:
Received 27 April 2014
Received in revised form 10 September 2014
Accepted 12 September 2014
Available online 17 September 2014
Editor: G.F. Giudice

ABSTRACT

We consider a decaying magnetic dark matter explaining the X-ray line at 3.55 keV shown recently from XMM-Newton observations. We introduce two singlet Majorana fermions that have almost degenerate masses and fermion–portal couplings with a charged scalar of weak scale mass. In our model, an approximate Z_2 symmetry gives rise to a tiny transition magnetic moment between the Majorana fermions at one loop. The heavier Majorana fermion becomes a thermal dark matter due to the sizable fermion–portal coupling to the SM charged fermions. We find the parameter space for the masses of dark matter and charged scalar and their couplings, being consistent with both the relic density and the X-ray line. Various phenomenological constraints on the model are also discussed.

1. Introduction

Dark matter is a dominant component of the matter density in the universe, playing a crucial role in the structure formation and explaining the flatness of galaxy rotation curves, etc. The evidences for dark matter are without question but there is no understanding of the properties of dark matter such as its mass or coupling to the SM particle, except gravitational interaction.

Recently, there was an interesting indication of dark matter [1] from the stacked X-ray spectrum of galaxies and clusters [2], which shows an unexplained line signal at the energy 3.55 keV. A sterile neutrino having a very small mixing with the active neutrinos, can explain the X-ray line signal by a small transition magnetic moment but the link to the generation of neutrino masses via see–saw mechanism is unclear due to a small mixing [1]. The model building issue with keV sterile neutrino was discussed in Ref. [3]. There have been more candidates suggested for dark matter after the X-ray line was identified [4].

In this work, we consider a decaying dark matter model with two Majorana fermions. Similarly to the sterile neutrino case, the X-ray line can be obtained from the decay of the heavier Majorana fermion, for a sufficiently small magnetic transition dipole moment and a mass difference of 3.55 keV between the two Majorana fermion masses. To this purpose, we propose a microscopic model for dark matter containing the fermion–portal couplings with a new charged scalar [5,6]. We introduce an approximate Z_2 symmetry for the long-lived dark matter and a $U(1)_X$ global symmetry for controlling the Z_2 breaking to a small amount. As a consequence, a fermion–portal coupling for the heavier Majorana fermion preserves Z_2 and is sizable while a tiny coupling for the lighter Majorana fermion is produced after an explicit breaking of Z_2. Then, when fermion–portal couplings break CP, a tiny transition magnetic moment between two Majorana fermions is degenerated at one loop [7], even for the charged scalar of weak scale mass. Therefore, the heavier Majorana fermion is sufficiently long-lived for explaining the X-ray line and it can be thermally produced due to the sizable fermion–portal coupling to the SM charged fermion.

We study the parameter space for the masses and couplings of dark matter and the charged scalar, that are consistent with both the X-ray line and the dark matter relic density in our model. We also discuss the phenomenological constraints on the model, coming from indirect and direct detection experiments, precision measurements such as the anomalous magnetic moment of muon, and collider experiments.

The paper is organized as follows. We begin with the properties of magnetic dark matter explaining the X-ray line and describe a microscopic model for the magnetic dark matter in a simple extension of the SM with a charged scalar. Then, we impose the condition for the relic density in our model and discuss the compatibility with the X-ray line signal. Next, various phenomenological constraints on the model are given. Finally, conclusions are drawn.

2. Magnetic dark matter and X-ray line

We consider a magnetic dipole operator for Majorana fermion dark matter and discuss the required properties for explaining the cluster X-ray line at 3.55 keV.

http://dx.doi.org/10.1016/j.physletb.2014.09.031

For two singlet Majorana fermions, χ_1 and χ_2, having masses m_{χ_1} and m_{χ_2}, respectively, we introduce an effective transition magnetic operator between them as

$$\mathcal{L} = \frac{m_{\chi_2}}{\Lambda^2}\bar{\chi}_2 i\sigma^{\mu\nu}\chi_1 F_{\mu\nu} + \text{h.c.} \tag{1}$$

with Λ being the effective cutoff scale. Then, for $m_{\chi_2} > m_{\chi_1}$, the decay rate of the heavier Majorana fermion into the light one and a photon is

$$\Gamma(\chi_2 \to \chi_1 + \gamma) = \frac{m_{\chi_2}^5}{2\pi\Lambda^4}\left(1 - \frac{m_{\chi_1}^2}{m_{\chi_2}^2}\right)^3 = \frac{4m_{\chi_2}^2}{\pi\Lambda^4}E_\gamma^3 \tag{2}$$

where in the second line, use is made of the photon energy given by

$$E_\gamma = \frac{1}{2}m_{\chi_2}\left(1 - \frac{m_{\chi_1}^2}{m_{\chi_2}^2}\right). \tag{3}$$

Thus, the larger the dark matter mass, the more tuning we need between Majorana masses for $E_\gamma = 3.55$ keV. For instance, for $m_{\chi_2} = 10$ GeV, we need $|\Delta m/m_{\chi_2}| = 3.55 \times 10^{-7}$ with $\Delta m \equiv m_{\chi_2} - m_{\chi_1}$. For a 3.55 keV dark matter, the necessary value of the lifetime of dark matter for the X-ray line is $\tau_{\rm DM} = 0.20\text{–}1.8 \times 10^{28}$ s [1], which is equivalent to $\Gamma_{\rm DM} = 0.36\text{–}3.3 \times 10^{-52}$ GeV. For $m_{\chi_2} = 10$ GeV, assuming that χ_2 occupies the whole dark matter relic density,[1] the necessary lifetime of dark matter is rescaled to $\tau_{\chi_2} = 0.14\text{–}1.3 \times 10^{22}$ s and the decay width of dark matter is $\Gamma_{\chi_2} = 0.51\text{–}4.6 \times 10^{-46}$ GeV, so the required suppression scale of the magnetic dipole operator is then given by $\Lambda = (0.59\text{–}1.0) \times 10^8$ GeV.

When $\chi_1 = \nu$ is the SM neutrino and $\chi_2 = \nu_s$ is a sterile neutrino, a large suppression factor necessary for the X-ray line can be attributed to a small Yukawa coupling for the sterile neutrino. It has been shown that the 3.55 keV X-ray line can be obtained for a small mixing angle between the SM neutrino and the sterile neutrino, $\theta^2 \simeq \frac{m_\nu}{m_s} \sim 10^{-11}$, and the sterile neutrino mass, $m_s = 7.1$ keV [1].

3. Microscopic origin of magnetic dark matter

In this section, we consider a simple model for generating a tiny magnetic dipole moment for dark matter discussed in the previous section.

The minimal setup to obtain the magnetic dipole operator for dark matter is to introduce only a charged scalar ϕ, that couples between two Majorana singlet fermions, χ_1 and χ_2, and the SM $SU(2)_L$-singlet charged fermion ψ_R, the so called fermion–portal couplings [5,6], as follows,

$$-\mathcal{L}_{\rm DM} = (\epsilon\bar{\psi}P_L\chi_1\phi + \lambda\bar{\psi}P_L\chi_2\phi + m_\psi\bar{\psi}_R\psi_L + \text{c.c.}) + m_\phi^2|\phi|^2 + \frac{1}{2}m_{\chi_1}\overline{\chi_1}\chi_1 + \frac{1}{2}m_{\chi_2}\overline{\chi_2}\chi_2 + \left(\frac{1}{2}\delta\,\overline{\chi_1}\chi_2 + \text{c.c.}\right) \tag{4}$$

where the electromagnetic charges are $q_{\psi_R} = q_\phi = -1$ for charged leptons, $q_{\psi_R} = q_\phi = +\frac{2}{3}$ or $-\frac{1}{3}$ for up or down-type quark, and ψ_L is the left-handed part of the SM charged fermion belonging to an $SU(2)_L$ doublet.

We introduce a Z_2 discrete symmetry under which χ_2 and ϕ are odd while χ_1 is even. In this case, we get $\epsilon = \delta = 0$ in the Lagrangian (4). Moreover, we add a $U(1)_X$ global symmetry under which $\chi_1 \to e^{i\alpha\gamma^5}\chi_1$, $\chi_2 \to e^{-i\alpha\gamma^5}\chi_2$, and $\phi \to e^{i\alpha}\phi$ while ψ does not transform. Then, the tree-level Majorana masses for χ_1 and χ_2 are forbidden, that is, $m_{\chi_1} = m_{\chi_2} = 0$. We also introduce a singlet complex scalar S that transforms as $S \to e^{-2i\alpha}S$ under the $U(1)_X$ global symmetry and is Z_2-even. The hyper charges, $U(1)_X$ charges and Z_2 parities are summarized in Table 1.

Table 1
Hypercharges, $U(1)_X$ charges and Z_2 parities in our model.

	ψ_R	χ_{1L}	χ_{2L}	ϕ	S
$U(1)_Y$	q_{ψ_R}	0	0	q_{ψ_R}	0
$U(1)_X$	0	$+1$	-1	$+1$	-2
Z_2	$+$	$+$	$-$	$-$	$+$

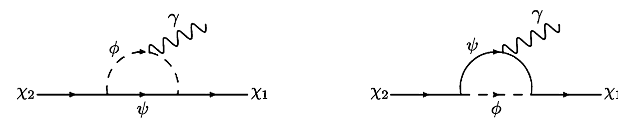

Fig. 1. Feynman diagrams relevant for the decay of dark matter.

After the S scalar gets a nonzero VEV and then the $U(1)_X$ symmetry is broken spontaneously, we obtain the Majorana masses as well as the Yukawa coupling as follows,

$$-\mathcal{L}_S = \frac{1}{2}y_1 S\bar{\chi}_1 P_L\chi_1 + \frac{1}{2}y_2 S^*\bar{\chi}_2 P_L\chi_2 + \frac{\kappa}{\Lambda_{UV}}S\bar{\psi}P_L\chi_1\phi + \text{c.c.} \tag{5}$$

where the last term preserves the $U(1)_X$ but it breaks the Z_2 symmetry explicitly at the UV cutoff scale Λ_{UV} so it is the source for making dark matter to decay. Then, for $\langle S\rangle \neq 0$, we get $m_{\chi_{1,2}} = y_{1,2}\langle S\rangle$ and $\epsilon = \kappa\langle S\rangle/\Lambda_{UV}$. For instance, for $\langle S\rangle = 100$ GeV (100 TeV), $\kappa = 0.1\text{–}1$ and $\Lambda_{UV} = 10^8\text{–}10^{11}$ GeV ($10^{11}\text{–}10^{14}$ GeV), we get $|\epsilon| \sim 10^{-9}\text{–}10^{-7}$ and $m_{\chi_{1,2}} \sim 100$ GeV for $y_1 \sim y_2 \sim 1$ (10^{-4}). Henceforth, having in mind the above microscopic model with an approximate Z_2 symmetry, we assume that $\delta = 0$ and $|\epsilon| \ll 1$ in the Lagrangian (4).

We note that there exists a Goldstone boson (the imaginary part of S) after the $U(1)_X$ symmetry is broken spontaneously. The Goldstone boson can get mass due to QCD-like anomalies in the hidden sector or an explicit breaking of the $U(1)_X$ symmetry. For instance, for $\langle S\rangle \sim 100$ TeV and the hidden QCD scale $\Lambda \sim 10$ TeV, one can obtain the mass of the Goldstone boson by $m_a \sim \frac{\Lambda^2}{\langle S\rangle} \sim 1$ TeV. The Goldstone boson couples to the SM fermion via a higher dimensional operator in Eq. (5). As the charged scalar decays mostly to a SM fermion and dark matter by fermion portal coupling, the Goldstone interaction to the SM could not be seen at the collider. But, we will comment on the effect of the Goldstone interaction on the cosmological predictions for dark matter in the next section.

Computing the one-loop corrections (see Fig. 1) and taking $m_{\chi_2} \approx m_{\chi_1}$, we obtain the effective transition magnetic moment operator for dark matter as

$$\mathcal{L}_{mdm} = \frac{ef_\chi}{2m_{\chi_2}}\bar{\chi}_2 i\sigma^{\mu\nu}\chi_1 F_{\mu\nu} \tag{6}$$

where

$$f_\chi = N_c\frac{{\rm Im}(\epsilon^*\lambda)}{16\pi^2}m_{\chi_2}^2\left[\int_0^1 dx\,\frac{q_\phi x^2(1-x)}{m_{\chi_2}^2x^2 + (m_\phi^2 - m_{\chi_2}^2)x + m_\psi^2(1-x)} + \int_0^1 dx\,\frac{q_{\psi_R}x^2(1-x)}{m_{\chi_2}^2x^2 + (m_\psi^2 - m_{\chi_2}^2)x + m_\phi^2(1-x)}\right]$$

[1] If χ_1 contributes to the dark matter relic density too, the lifetime of the χ_2 particle must be smaller so that the suppression scale becomes smaller.