Magnetic dipole moment and keV neutrino dark matter

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Abstract

We study magnetic dipole moments of right-handed neutrinos in a keV neutrino dark matter model. This model is a simple extension of the standard model with only right-handed neutrinos and a pair of charged particles added. One of the right-handed neutrinos is the candidate of dark matter with a keV mass. Some bounds on the dark matter magnetic dipole moment and model parameters are obtained from cosmological observations.
1 Introduction

The evidences from neutrino experiments have established the neutrino oscillation phenomenon. The experimental data can be explained by flavor mixings of three (active) neutrinos, and oscillation probabilities are described by three generation mixing angles and two mass squared differences. The presence of non-vanishing neutrino masses means a necessity of physics beyond the standard model (SM). Furthermore, the smallness of neutrino mass squared differences compared with the charged fermion masses in the SM is one of striking properties of neutrinos. The type-I seesaw mechanism \[1\] is the most promising approach to explain such smallness of neutrino masses. In this mechanism, the sterile (right-handed) neutrinos are added to the SM. Since these sterile neutrinos are Majorana particles, they can have Majorana masses, which violate the lepton number. Consequently, the heavy enough Majorana masses of the sterile neutrinos can lead to tiny active neutrino masses.

On the other hand, the elucidation of the origin of dark matter (DM) \[2\], which governs about 23% of the energy density of the Universe \[3\], is also one of the most important goals in particle physics today. Recently, a large number of DM models have been discussed in the literature (e.g. see \[4\] for a recent review, and references therein). Among them, one of interesting candidates for DM is a sterile neutrino. In particular, models with three sterile neutrinos whose masses are below the EW scale have been proposed in \[5, 6, 7\]. Note that some astrophysical data possibly support the existence of sterile neutrinos \[8\].

In addition to a candidate for DM, the sterile neutrino can also play a role in other cosmological issues, such as the origin of the baryon asymmetry of the Universe (BAU). For instance, relatively heavy sterile neutrinos in the type-I seesaw mechanism can generate the BAU via leptogenesis \[9\]. The split seesaw mechanism \[10\] can give a hierarchical mass spectrum of sterile neutrinos, which can incorporate the usual leptogenesis with a keV sterile neutrino DM scenario.\[1\] A possible mass spectrum of sterile neutrinos to explain the BAU, DM, and MiniBooNE/LSND oscillation anomalies \[13\], as well as realize the tiny active neutrino masses, has been proposed in \[14\]. Clearly, the nature of neutrinos would be a key to find physics beyond the SM and understand some cosmological issues.

In this letter, we focus on the magnetic property of neutrinos. In particular, we concentrate on a simple extension of the SM \[15\], in which the right-handed neutrino magnetic moment can be generated by the interaction between new charged particles and sterile neutrinos. Note that the induced magnetic interaction could result in some interesting consequences for cosmology and high energy physics.

\[1\] See also \[11\] for discussions of the realistic flavor mixing in the mechanism.
2 Magnetic dipole moments

2.1 Active neutrinos

By introducing three generations of the right-handed neutrinos in the SM, the Yukawa interactions are given by

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} - (y_\nu \bar{L}_\nu R \Phi + \text{h.c.}), \]

where \( L, \nu_R, \) and \( \Phi \) are the left-handed lepton doublet, right-handed neutrino, and the SM Higgs, respectively. The Dirac neutrino mass is given by \( M_D = y_\nu v \), where \( v \) is the vacuum expectation value (VEV) of the Higgs.

The Dirac neutrino can have a magnetic dipole moment induced by radiative corrections [16] as

\[ \mu_{\nu_i} = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_i} \simeq 3 \times 10^{-19} \left( \frac{m_{\nu_i}}{1 \text{ eV}} \right) \mu_B, \]

where \( G_F \) is the Fermi constant, \( m_{\nu_i} \) are the corresponding (Dirac) neutrino mass eigenvalues, and \( \mu_B \) is the Bohr magneton, given by

\[ \mu_B = \frac{e}{2m_e} = 5.79 \times 10^{-9} \text{ eV \cdot Gauss}^{-1} = 1.93 \times 10^{-11} \text{ e cm}. \]

In Eq. (2), we have assumed \( m_\nu \simeq m_{\nu_i} \) as the typical neutrino mass scale. The current upper bounds on the neutrino magnetic moments for three flavors are given by the Borexino experiment as [17]

\[ \mu_{\nu_e} < 5.4 \times 10^{-11} \mu_B, \quad \mu_{\nu_\mu} < 1.5 \times 10^{-10} \mu_B, \quad \mu_{\nu_\tau} < 1.9 \times 10^{-10} \mu_B, \]

respectively. Note that a stronger bound on the typical neutrino dipole moment (\( \mu_\nu \)) is inferred in [18] from an estimate of effects on the core mass of the red giants at the helium flash as

\[ \mu_\nu < 3 \times 10^{-12} \mu_B \quad \text{with} \quad \mu_\nu^2 = \sum_{i,j=1}^{3} (|\mu_{ij}|^2 + |\epsilon_{ij}|^2), \]

where \( \mu_{ij} \) and \( \epsilon_{ij} \) are the elements of the magnetic and electric dipole matrices, respectively.

Here, we mention that the transition magnetic moment, which is relevant to \( \nu_i \to \nu_j + \gamma \), may exist for both Dirac and Majorana neutrino cases. Explicitly, one has [19]

\[ \mu_{ij}^D = \frac{3eG_F}{32\sqrt{2}\pi^2} (m_{\nu_i} + m_{\nu_j}) \sum_{\alpha=e,d,\tau} U_{ij}^\dagger U_{\alpha i} \left( \frac{m_\alpha}{m_W} \right)^2, \]
for the Dirac neutrinos, where $U$ and $m_\alpha$ are the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix and the corresponding charged lepton masses, respectively. If the neutrinos are Majorana particles, one can only have a flavor changing dipole operator,

$$\mathcal{L}_{\text{int}} = \mu_{ij}^M \nu_i C^{-1} \sigma_{\mu\nu} \nu_j F^{\mu\nu} + h.c.,$$

(7)

where $\nu_i$ are active neutrinos leading to the transition magnetic moments:

$$\mu_{ij}^M = \frac{3eG_F}{16\sqrt{2}\pi^2} (m_{\nu_i} + m_{\nu_j}) \sum_{\alpha=e,\mu,\tau} \text{Im} \left[ U^\dagger_{j\alpha} U_{\alpha i} \left( \frac{m_\alpha}{m_W} \right)^2 \right],$$

(8)

for the Majorana neutrinos.

### 2.2 Right-handed neutrinos

We now consider the magnetic moments of the right-handed neutrinos. If the neutrinos are Majorana particles, one can have the Majorana mass terms for the right-handed neutrinos, which violate the lepton number, with the Lagrangian, given by

$$\mathcal{L}_{\text{Majorana}} = -\frac{M_R}{2} \nu^c \nu R.$$

(9)

It is well known that the Lagrangians in Eqs. (1) and (9) give light active neutrino masses through the seesaw mechanism,

$$M_\nu = -M_D^T M_R^{-1} M_D,$$

(10)

after integrating out the heavy right-handed neutrinos. Note that $y_\nu$, $M_R$, $M_D$ and $M_\nu$ are all $3 \times 3$ matrices.

Since the right-handed (sterile) neutrinos are Majorana particles, only the transition magnetic moments can be induced, described by the following flavor changing dipole operator,

$$\mathcal{L}_{\text{int}} = \mu_{IJ}^N N_I C^{-1} \sigma_{\mu\nu} N_J F^{\mu\nu} + h.c..$$

(11)

There are some models to induce the magnetic moments of right-handed (sterile) neutrinos.

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2They describe the left-handed neutrinos as $\nu_{L\alpha} = U_{\alpha i} \nu_i + \theta_{\alpha I} N_I^c$ with the left-right mixing angles $\theta_{\alpha I} = (y_\nu)_{\alpha I} v / M_I$ and other mass eigenstates $N_I$ (so-called sterile neutrinos) almost corresponding to the right-handed neutrinos, i.e. $N_I \simeq \nu_{RI}$. Throughout this letter, indices $i, j = 1 \sim 3$ and $I, J = 1 \sim 3$ stand for generations of active and sterile neutrinos, respectively.
2.3 Neutrino dark matter model

Recently, Aparici, Santamaria, and Wudka (ASW) have proposed a model [15] which enlarges the SM by adding a negatively charged scalar, $\omega$, and one negatively charged vector-like fermion, $E$, with non-vanishing hypercharges, $Y(\omega) = -1$ and $Y(E) = -1$, in addition to the right-handed neutrinos. When one imposes a discrete symmetry, which affects only $\omega$ and $E$ as $\omega \rightarrow -\omega$ and $E \rightarrow -E$, the relevant Lagrangian allowed by the SM gauge and additional discrete symmetries is

$$L_{\text{ASW}} = L_{\text{SM}} + L_{\text{Majorana}} + L_K - L_Y - V,$$

where $V$ is the scalar potential for the SM Higgs and $\omega$.

In this model, 1-loop diagrams involving $\omega$ and $E$ contribute to the magnetic moments of the right-handed neutrinos. The same interactions also give rise to contributions to the right-handed neutrino Majorana masses through the operator $\xi(\Phi^\dagger\Phi)\bar{\nu}_R^c\nu_R$. An invisible Higgs decay through the interaction has been discussed in [15]. Moreover, it has been pointed out that the new charged particles can be produced at the CERN LHC experiment through the Drell-Yan process because of their charged properties if they are light enough. We further investigate DM properties of this kind of the model.

We now proceed with DM in the model. It is known that one of interesting neutrino DM models is the keV sterile neutrino DM model (e.g. see [6, 7, 21]). In this scenario, the lightest sterile neutrino with the keV mass is a decaying DM candidate. To be DM, the lifetime of the lightest sterile neutrino should be larger than the age of the Universe. The lightest sterile neutrino can radiatively decay into a photon ($\gamma$) and an active neutrino ($\nu_i$) through the left-right mixing.

Since we have new interactions which generate the right-handed neutrino magnetic moments, the lightest sterile neutrino can radiatively decay into $\gamma$ and $\nu_i$ with the decay width, given by

$$\Gamma_{N_1 \rightarrow \nu_i \gamma} = \frac{(M_1^2 - m_{\nu_i}^2)^2}{8\pi} |\mu_{1i}|^2 \simeq \frac{M_1^3}{8\pi} |\mu_{1i}|^2,$$

where $|\mu_{1i}|$ denotes the magnetic moment and $M_1$ is the mass of the (keV) sterile neutrino ($N_1$). Here, the active neutrino mass has been neglected in the second equality of Eq. (15). On the other hand, the keV sterile neutrino DM model also has a constraint from its decay

\[^3\text{See also [22] and [23] for general discussions on DM properties with the keV mass and neutrino energy loss in stellar interiors, respectively.}\]
into $\gamma$ and $\nu_i$ through the gauge boson and charged lepton loops with the left-right mixing angle. The decay width is given by

$$\Gamma_{N_1 \to \nu_i \gamma} = \frac{9\alpha G_F^2}{1024\pi^4} \sin^2(2\theta_1) M_1^5 \simeq 5.5 \times 10^{-22} \theta_1^2 \left( \frac{M_1}{\text{keV}} \right)^5 \text{s}^{-1},$$

where $\theta_1 \equiv \sum_{\alpha=e,\mu,\tau} (y_{\nu_\alpha})_{1\alpha} v / M_1$. Clearly, both decay mechanisms could produce a narrow line in the X-ray background [24, 25, 26]. As a result, for the latter case, the left-right mixing angle is restricted as $\theta_2 \lesssim 1.8 \times 10^{-5} (\text{keV} / M_1)^5$, equivalently $\Gamma_{N_1 \to \nu_i \gamma} \lesssim (10^{-28} - 10^{-26}) \text{s}^{-1}$ in a region of the emission photon energy $0.5 \text{ keV} \leq E_\gamma \leq 12 \text{ keV}$ given in [26] for $\Gamma_{N_1 \to \nu_i \gamma}$. The emission photon energy is related with the decaying sterile neutrino mass as $E_\gamma = M_1 / 2$. For $\Gamma_{N_1 \to \nu_i \gamma} \lesssim 10^{-28} \text{s}^{-1}$, one obtains

$$|\mu_{1i}| \lesssim 3.89 \times 10^{-16} \mu_B,$$

where $M_1 = 5 \text{ keV}$ has been used.\(^4\) It is seen that the constraint in Eq. (17) on the neutrino magnetic moment is much stronger than the one from the consideration of the red giants in Eq. (5). Note that Eq. (5) is obtained from the discussion of the plasmon decay into neutrinos where the masses of neutrinos are lower than $\mathcal{O}(\text{keV})$. Therefore, once the sterile neutrinos have magnetic interactions mediated by new particles, the keV sterile neutrino DM scenario should satisfy the constraint in Eq. (17), which is model-independent [15], rather than the one from the red giants.

We now investigate the neutrino magnetic moment in a model-dependent way. The magnetic moment $|\mu_{1i}|$ induced from the model in Eq. (12) is calculated as

$$|\mu_{1i}| = \frac{g' f(r)}{2(4\pi)^2 M_E} \sum_{J=2,3} \sum_{\alpha=e,\mu,\tau} \text{Im}[h_1^* h_J \theta_J \alpha U_{\alpha i}],$$

$$f(r) = \frac{1}{1 - r} + \frac{r}{(1 - r)^2} \log(r),$$

for the case of $M_1 \ll M_E$ and $M_\omega$ with $r \equiv M_\omega^2 / M_E^2$. Here, the active neutrino as the final state is converted from the internal sterile state $N_J \simeq \nu_{RJ}$ ($J = 2, 3$) through the corresponding left-right mixing $\theta_{J\alpha}$. Since the Majorana neutrinos can only have the transition magnetic moments, the sum of $J$ is performed for $J = 2$ and 3. The external momenta and masses can be neglected as in [15].

Two of three sterile neutrinos can generically play a role to realize the active neutrino mass scales through the seesaw mechanism in the keV sterile neutrino DM model, e.g. [1].

\(^4\) $\Gamma_{N_1 \to \nu_i \gamma} \lesssim 10^{-26} \text{s}^{-1}$ is also allowed for $M_1 \simeq 24 \text{ keV}$. In this case, a more severe bound $|\mu_{1i}| \lesssim 3.70 \times 10^{-16} \mu_B$ can be derived.
Therefore, the left-right mixing angle for the corresponding generations can be described by the typical active neutrino mass scale $m_\nu$ and two heavier sterile neutrino mass scales $M_{2,3}$, given by $\theta_{J\alpha} = \sqrt{m_\nu/M_{2,3}}$. On the other hand, since the Yukawa coupling of the lightest sterile neutrino to the left-handed lepton doublet and SM Higgs should be tiny, the sterile neutrino DM with the keV mass is not responsible for the active neutrino mass scales. Because of this smallness of the Yukawa coupling, the keV sterile neutrino cannot be in the equilibrium even at a high temperature. This feature is crucial for the various production mechanisms of the keV sterile neutrino DM with the correct abundance [10, 27, 28, 29].

We now explicitly examine a specific and economical model [6, 7] with right-handed neutrinos and new charged particles as an example. In this model, one of heavier sterile neutrinos is in the thermal equilibrium before the sphaleron process becomes inactive [30]. When the Yukawa coupling of the remaining heavier sterile neutrino is naively estimated as $(y_{\nu 2})^2 \sim \sqrt{\Delta m_{\text{sol}} M_2/v^2} \sim O(10^{-15})$, the sterile neutrino is out of equilibrium at the time without the sphaleron process. The $2 \leftrightarrow 2$ interactions among the right-handed neutrinos and new charged particles, such as the scalar exchange $\nu_R E \leftrightarrow \nu_R E$ interaction, are important for the condition of the non-equilibrium of DM. The rates of those new interactions are described by the new Yukawa couplings $h_I$ given in Eq. (13), where $I$ denotes the generation of the right-handed neutrinos. Note that these Yukawa couplings do not affect the active neutrino masses. When $|h_I|^2 \lesssim O(10^{-14})$, the corresponding sterile neutrino is out-of-equilibrium at the time when the sphaleron process becomes ineffective. Under these discussions, we impose $\Gamma_{N_1 \rightarrow \nu_i \gamma}^{\text{mag}} \lesssim 10^{-28} \text{ s}^{-1}$ on Eq. (17) with Eqs. (18) and (19). Then, we obtain a constraint on the model parameter as

$$M_E \geq 24.3 \text{ MeV},$$

where we have taken that $g' = 0.35$, $f(r) = 1/2$, $\theta_{J\alpha} = \sqrt{m_\nu/M_{2,3}}$, $m_\nu = 0.01 \text{ eV}$, $M_{2,3} = 10 \text{ GeV}$, and $\text{Im}[h_1 h_3 U_{\alpha i}] = 5 \times 10^{-9}$. Note that these values can satisfy the above conditions in the keV sterile neutrino DM model realizing the BAU via the oscillation of the heavier sterile neutrino with a mass spectrum of $(M_1, M_2, M_3) = (\text{keV}, O(1 - 10) \text{ GeV}, O(1 - 10) \text{ GeV})$. Note also that $f(r) \rightarrow 1/2$ if $M_\omega/M_E \rightarrow 1$. It is clear the constraint in Eq. (20) is much weaker than that from high energy experiments in the presence of the new charged particles. In other models of the BAU, the constraint on the model parameters becomes weaker because of the largeness of the heavier sterile neutrino masses.
3 Summary

We have investigated the magnetic dipole moments in the keV sterile neutrino DM model. In this DM model, the lightest sterile neutrino with the keV scale mass is a decaying DM candidate with its lifetime greater than the age of the Universe. Since the width of the radiative DM decay into a photon and an active neutrino is constrained by X-ray observations, we have obtained a model-independent constraint on the magnetic interactions, leading to $|\mu_{1i}| \lesssim 3.89 \times 10^{-16} \mu_B$ for $M_1 = 5$ keV, which is stronger than the bound from the consideration of the plasmon decay in the red giants. We have also studied the magnetic dipole moment in a model-dependent way. Explicitly, the same condition from the X-ray observations gives a constraint of $M_E \gtrsim 24.3$ MeV in the model of baryogenesis from the heavier right-handed neutrino oscillation.

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