A simple model for magnetic inelastic dark matter (MiDM)

Sudhanwa Patra\textsuperscript{1,2,*} and Soumya Rao\textsuperscript{1,†}

\textsuperscript{1}Physical Research Laboratory, Ahmedabad 380009, India
\textsuperscript{2}Institute of Physics, Bhubaneswar 751005, India

Abstract

A simple model for magnetic inelastic dark matter (MiDM), which is a minimal extension of the standard model with right-handed neutrinos ($N_R$), a singly charged scalar ($S$) and a vector-like charged fermion ($E$), has been presented. In this framework in which dark matter inelastically scatters off nuclei through a magnetic dipole interaction by making a transition to a nearly degenerate state with a mass splitting ($\delta$) of 100 keV. The model is constrained from Direct detection experiments, DAMA and COGENT. In our analysis we do not find any parameter space using the recent annual modulation data from COGENT, where DAMA and COGENT are consistent with each other. The bound from relic density provides a much stronger constraint. We find that this minimal extension of SM incorporates a DM candidate which can explain the indirect detection results while being consistent with relic density measurements. The right handed neutrino and the charged particles responsible for the right-handed neutrino magnetic moments could be produced at the Large Hadron Collider.

\textsuperscript{*}Electronic address: sudha.astro@gmail.com
\textsuperscript{†}Electronic address: soumya@prl.res.in
I. INTRODUCTION

The quest for the identification of dark matter (DM), together with the comprehension of the nature of dark energy, is one of the most challenging problems in the understanding of the physical world. A canonical model for Dark Matter (DM) utilizing the existence of Weakly Interacting Massive Particles (WIMPs) has emerged. On the other hand, supersymmetric extensions of the Standard Model naturally incorporate such stable particles, like for example the neutralino. The observed DM density, set by thermal freeze-out, determines the cross-section to annihilate to Standard Model (SM) fields to be a value typical of weak scale physics \(\langle \sigma v \rangle \simeq 3.6 \times 10^{-26}\text{cm}^3/\text{sec} \). Within the paradigm of these models, many phenomenological expectations have been fixed, including the annihilation modes to the SM interaction channels with corresponding rates for indirect detection in the galaxy today.

Cosmological observations strongly suggest that non-luminous, non-baryonic matter constitutes most of the dark matter in the universe. This dark matter should be distributed in dark halos of galaxies such as the Milky Way, enabling the direct detection of the dark matter particles via their interactions in terrestrial detectors. Recently, inelastic dark matter (IDM) is a viable scenario to explain DAMA consistent with the other experiments. The inelastic scenario assumes that WIMPs (\(\chi\)) can only scatter off baryonic matter (N) by transition into an excited state at a certain energy above the ground state (\(\chi N \rightarrow \chi^* N\)), while elastic scattering is forbidden or highly suppressed.

Since neutrinos have very weak interactions, any additional interaction, like the one provided by magnetic moments, could have dramatic consequences in their behaviour. As a result, neutrino magnetic moments provide new photon-neutrino couplings which affect the production and detection of neutrinos at colliders and large transition magnetic moments could affect neutrino oscillation. The magnetic moments of right-handed neutrinos arise as dimension 5-operators which is the same dimension as of the well-known Weinberg operator that is often used to parametrize neutrino masses. It is therefore natural to consider right-handed neutrino magnetic moments as the first manifestation of non-trivial electromagnetic properties of neutrinos. Among important low-energy properties of WIMPs are their electromagnetic form factors. It has been known for a long time that the possibility of charged WIMPs is strongly disfavored [1, 2] and stringent limits exist in the case of a fractional charge [3].
Motivated by the discussion above we present here a very simple model which gives rise to right-handed neutrino magnetic moments; it includes, in addition to the SM fields and the right-handed neutrinos, a charged scalar singlet and a charged singlet vector-like fermion. While the phenomenological effects of an effective magnetic coupling of right-handed neutrinos have their own intrinsic interests, their observation would also indicate the presence of physics beyond the SM, and it is therefore natural to determine the types of new particles and interactions that would be implied by the observation of such effective couplings. There is, of course, a certain amount of freedom in constructing models based on the single constraint that Majorana magnetic couplings be generated at the one loop level, but the simplest possibility, involving the introduction of one charged heavy scalar and one charged heavy fermion, involves the basic features of more general models and addresses the main problems such theories face. In addition, if the right-handed neutrino magnetic moments are large the new particles should be relatively light and could be produced and analysed at the Large Hadron Collider (LHC) or the International Linear Collider (ILC). This is also a general feature of models with large right-handed neutrino magnetic moments.

Recently there has been a lot of excitement in the field of Dark Matter with the observation of an annual modulation signal by COGENT [4], similar to what has been reported consistently by DAMA [5] over several years. An excess in cosmic ray positron and electron signals over the expected background as observed by PAMELA [6] and FERMI [7] may be a signal of annihilating Dark matter for the energy of $O(100)$ GeV. The annihilation cross-section needed to produce these signals is non-thermal, a factor of $\sim 10 - 1000$ (depending on DM mass and astrophysical boost factor) large than the thermal annihilation cross-section [8, 9]. One possibility is to add new particles and these particles mediate a Sommerfeld enhancement, implying boosted annihilation in the halo today, while also acting as intermediate final states, thereby allowing SM particles produced from DM annihilations.

The paper is organised as follows. In section-II, we present a simple model implementing inelastic dipolar dark matter which is a simple extension of the Standard model for the dipolar dark matter to satisfy both observational and experimental bounds. In the following section-III, we introduce the effective lagrangian for the magnetic inelastic dark matter (MiDM) interaction with a photons. We discuss how one can large magnetic dipole moment for heavy Majorana neutrino which is assumed to be dark matter candidate in our model and analytical expressions are presented in section III. We discuss the relic abundance
in section IV. Section V presents constraints on dark matter dipole moments and masses that arises from direct search detectors DAMA and COGENT. Comparison with the indirect detection experiments PAMELA and FERMI is discussed in section VI. Finally, we present our summary of our whole work in section VII.

II. MODEL

Beside the standard model particles and right-handed Majorana neutrinos, the model contains a singly charged scalar and three vectorlike singly charged fermions. The new fermions are assumed to be vector like to make sure that the theory is anomaly free as for self consistency. The quantum numbers of these extra particles under $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge group : $N_R \equiv (1, 1, 0)$, $S \equiv (1, 1, 0)$ and $E \equiv (1, 1, 0)$ and their $Z_2$ assignment is shown in Table: [I]. The hypercharge assignment is done by the relation $Y = Q - I_3$.

| Field   | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | $Z_2$ |
|----------|---------------------------------------|-------|
| Fermions | $Q_L \equiv (u, d)_L^T$               | (3, 2, 1/6) | +   |
|          | $u_R$                                 | (3, 1, 2/3) | +   |
|          | $d_R$                                 | (3, 1, -1/3) | +   |
|          | $\ell_L \equiv (\nu, e)_L^T$          | (1, 2, -1/2) | +   |
|          | $e_R$                                 | (1, 1, -1) | +   |
|          | $E$                                   | (1, 1, -1) | -   |
|          | $N_R$                                 | (1, 1, 0) | -   |
| Scalars  | $\Phi$                                | (1, 2, +1/2) | +   |
|          | $S^+$                                 | (1, 1, +1) | +   |

We first analyze the case when the DM candidate is a fermion we denote by $\chi$, which is assumed to be odd under $Z_2$, and a gauge singlet; we will also assume that $\chi$ has no chiral interactions. In this model, the Yukawa terms of the lepton sector would be

...
\[
\mathcal{L} = -\left[ Y_S (N_R)^c \bar{E} S^+ + Y'_S \bar{N}_R E S^+ + h.c. \right] \\
- \left[ \frac{1}{2}(N_R)C M_N N_R - M_E \bar{E}_L E_L + h.c. \right] + V(\phi, \chi)
\]

where \( Y_S \) is the new Yukawa couplings, \( M_R \) and \( M_E \) are the mass matrices of \( N_R \) and \( E_L \).

In the unitary gauge the Higgs doublet is given by

\[
\Phi = \frac{H + v}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \end{pmatrix}
\]

where \( H \) is the SM Higgs boson and \( v = 246 \) GeV is the vacuum expectation value. All through this study we will choose \( M_H = 120 \) GeV.

The general scalar potential contains the quadratic and quartic terms as below

\[
V(\Phi, S) = -m_1^2 (\Phi^\dagger \Phi) + \lambda_1 (\Phi^\dagger \Phi)^2 + m_2^2 (S^\dagger S) + \lambda_2 (S^\dagger S)^2 \\
+ \frac{\lambda_3}{2} (S^\dagger S) (\Phi^\dagger \Phi)
\]

where the mass of the singly charged scalar is \( m_S^2 = m_2^2 + \lambda_2 v^2 \).

### III. MAGNETIC INELASTIC DARK MATTER (MiDM)

In this section, we focus on magnetic inelastic dark matter (MiDM), because it has a unique and interesting directional signature and it has been shown that MiDM could explain both DAMA and other null results [10]. The model takes advantage of both the magnetic moment and large mass of iodine. In [11] the velocity dependent scattering resulting from magnetic dipole operator is said to explain simultaneously DAMA and COGENT results as well as null results from other experiments. Explicit formula for scattering cross section assuming magnetic dipole operator has been derived in [12].

In MiDM, the dark matter couples off-diagonally to the photon:

\[
\mathcal{L} \ni -\frac{\mu \chi}{2} \bar{\chi} \sigma_{\mu\nu} \mathcal{F}^{\mu\nu} \chi
\]
where mass of $\chi$ and $\chi^*$ are split by $\delta = 100$ keV. The off-diagonal coupling is natural if the dark matter is a Majorana fermion. In the present scenario, heavy Majorana neutrino is a candidate for magnetic inelastic dark matter (MiDM). Due to the Majorana nature, the magnetic moment of heavy Majorana neutrinos is zero. There is only transition magnetic moment for them. The effective Lagrangian for coupling of a heavy Majorana neutrino with a magnetic dipole moment $\mu$

$$\mathcal{L}_{edm} = -\frac{i}{2} \bar{N}_k \sigma_{\mu\nu}(\mu_{jk}) N_j \mathcal{F}^{\mu\nu}$$

where $\mu_{jk}$ is the transition magnetic dipole moment.

![Diagram](image-url)

**FIG. 1**: Contributing diagram for the heavy right handed Majorana neutrino

### A. Magnetic moment of heavy RH Majorana neutrino

In the model considered, we have four diagrams contributing to the transization magnetic moment, which are depicted in Fig.(1): (a and b) a loop with the $B$ gauge boson attached to the $E$ and (c and d) a loop with the $B$ gauge boson attached to the scalar $S$.

The Yukawa interactions of heavy Majorana neutrinos with $\chi$ and $E$ can be rewritten in the following way.
\[
\frac{1}{2} \left[ N_\alpha^C S^-(Y^T)_{\alpha i} P_R E_j^C + N_\alpha S^+(Y^\dagger)_\alpha P_L E_j \right] + \frac{1}{2} \left[ \overline{E}_j Y_{i \alpha} S^- P_R N_\alpha + \overline{E}_j^C (Y^*)_{i \alpha} S^+ P_L N_\alpha^C \right],
\]
through which we can derive relevant Feynman rules.

Assuming that heavy Majorana neutrinos are nearly degenerate, i.e., \( M_\alpha \approx M_\beta \approx M_R \), we derive the expression of \( \mu(0) \):

\[
\mu_{\alpha \beta}(0) = \frac{M_R}{64 \pi^2} \left[ (Y_{S}^\dagger)_{\beta i} (Y_S)_{i \alpha} - (Y_{S}^T)_{\beta i} (Y^*_S)_{i \alpha} \right] \left[ I(M_S^2, M_R^2, M_{E_j}) - I(M_{E_j}, M_R^2, M_S^2) \right],
\]
with

\[
I(A, B, C) = \int dx \frac{x(1-x)^2}{(1-x)A + x(x-1)B + xC},
\]

where \( M_{E_j} \) and \( M_S \) are the mass eigenvalues of heavy vector-like fermion \( E \) and singly charged scalar \( S \), respectively. In simplest form, one can write as

\[
\mu_{\alpha \beta}(0) \sim \frac{1}{32 \pi^2} (Y_{S}^\dagger)_{\beta i} (Y_S)_{i \alpha} \frac{e}{M_E} F(x)
\]

where \( F(x) = \frac{1}{1-x} + \frac{x}{(1-x)^2} \ln(x) \), \( x = \frac{M_S^2}{M_E^2} \). Non-perturbative limit gives us \((Y_{S}^\dagger Y_S) \leq 4\pi\). With this spectrum, one can get the magnetic moment of the order of \(10^{-7} \mu_B\) to \(10^{-9} \mu_B\).

**B. Cross-section RH neutrino through \( e^+ e^- \to \gamma, Z^* \to \nu_k \nu_j \ (k \neq j) \)**

The most dramatic effect of a large magnetic dipole moment of a heavy neutrino will be in the production cross section and angular distribution. Though the discussion of the differential cross section for a heavy charged lepton can be found in work of Sher [13], here we only discuss qualitatively how one can produce RH Majorana neutrinos in near future experiment within our framework. In the discussion of Escribano and Masso [14], one can write a \( U(1) \) invariant operator as:

\[
\mathcal{N}_{Rj} (\mu_{N}^{jk} + i \mathcal{D}_{N}^{jk}) \sigma_{\alpha \beta} N_{Rk}^\dagger B^{\alpha \beta},
\]

where \( B^{\alpha \beta} \) is the \( U(1) \) field tensor. This gives a coupling to the photon, which we define to be the EDM, as well as a coupling to the \( Z \) which is the EDM times \( \tan \theta_W \). When we include the effect of \( Z \) coupling to \( N \) in the differential cross section, it turns out that the contribution has very little effect on the result.
The differential cross-section for the process, $e^+e^- \rightarrow \gamma, Z^* \rightarrow N_k N_j (k \neq j)$, is given by

$$
\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} \sqrt{1 - \frac{4M^2}{s}} \left( F_1 + \frac{1}{8\sin^2 2\theta_W} P_{\gamma Z} F_2 \right) \\
+ \left( \frac{(1 - 4\sin^2 \theta_W) \tan \theta_W}{\sin^2 2\theta_W} P_{\gamma Z} F_3 \right)
$$

where the values of $F_1, F_2, F_3, P_{ZZ}$ and $P_{\gamma Z}$

$$
F_1 = \mu_N^2 s \sin^2 \theta \left( 1 + \frac{4M^2}{s} \right), \\
F_2 = 1 + \cos^2 \theta - \frac{4M^2}{s} \sin^2 \theta + 8C_V \cos \theta \\
+ \mu_N^2 s \tan^2 \theta_W \left[ \sin^2 \theta + \frac{4M^2}{s} \left( 1 + \cos^2 \theta \right) \right], \\
F_3 = 4\mu_N^2 s \left[ \sin^2 \theta + \frac{4M^2}{s} \left( 1 + \cos^2 \theta \right) \right], \\
$$

$$
P_{ZZ} = \frac{s^2}{(s - M_Z^2)^2 + \Gamma^2 M_Z^2}, \\
P_{\gamma Z} = \frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + \Gamma^2 M_Z^2},
$$

with $\mu_{Nj}^2$ is the transition magnetic moment of heavy Majorana neutrino, $C_V = \frac{1}{2} - 2\sin^2 \theta_W$, and we have dropped the numerically negligible $C_V^2$ terms, for simplicity.

C. Mass splitting between two Majorana neutrino component

In this paper we shall not discuss the origin of the small mass differences between the degenerate right-handed neutrinos, but for completeness we demonstrate that a mass splitting of the order of $10^{-7}$ GeV is not completely unnatural for 100 GeV scale right-handed neutrinos. Consider a diagram with a vertex $\lambda_3 (\Phi^\dagger \Phi)(S^\dagger S)$ attached to the singly charged scalar $S$ which runs in loop and this kind of diagram gives a finite contribution to the mass splitting. The diagram with a vertex $\lambda_3 (\Phi^\dagger \Phi)(S^\dagger S)$ attached to the $S$ field (which is shown in fig:(3) give a finite contribution to the mass splitting as:

$$
\Delta M_R \sim \frac{\lambda_3 Y_S^2 Y_S \langle \Phi \rangle^2}{(4\pi)^2 4M_E} \lambda_3 \Phi
$$

For the mass of the charged lepton to be around 100 GeV (i.e, $M_E \sim 100$-150 GeV), $\langle \Phi \rangle=100$ GeV and $Y_S^2 \sim 1 - 10$, one can write

$$
\Delta M_R \sim \frac{10^5}{64\pi^2 M_E} \lambda_3 \Phi
$$
FIG. 2: The total cross section for heavy right handed neutrino $e^+ e^- \rightarrow \gamma, Z \rightarrow N_k N_j \ (k \neq j)$ for various EDMs, in units of Bohr magneton. The cross section is shown as a function of center of collider energy $\sqrt{s}$ and here we have varied the masses of heavy right handed neutrino as $M = 100, 160, 250, 400, 500$ GeV from the top to the bottom curves.

FIG. 3: Mass splitting between the dipolar dark matter (DDM) and its companion partner $S$

Now one can easily get the mass splitting between two right handed neutrinos of the order of $O(10^{-4})$ GeV. If we thus start with a symmetry to get a 100 GeV Scale degenerate right-handed neutrinos, after the symmetry breaking, we get a mass splitting between the companion states of right-handed neutrinos to be in the range of $O(10^{-4})$ GeV or 100 keV range, naturally through radiative corrections.
IV. DARK MATTER ANNIHILATION AND RELIC ABUNDANCE

To calculate the relic abundance we solve the Boltzmann equation for heavy Majorana neutrino which is assumed to be a Dipolar Dark Matter candidate, given by [15]

\[ \frac{dn_\chi}{dt} + 3H n_\chi = -\langle \sigma v \rangle [n^2_\chi - n^2_{\chi,\text{eq}}] \]

where \( H \) is the Hubble parameter, \( n_\chi \) is the number density of Dipolar Dark Matter (\( \chi \)), \( n^2_{\chi,\text{eq}} \) is the equilibrium number density, \( v \) is the relative velocity and \( \langle \sigma v \rangle \) is the thermal average of the annihilation cross-section \( \chi \chi \rightarrow \text{all} \).

Since the Dipolar Dark Matter considered in our model is non-relativistic, the equilibrium number density is

\[ n_{\chi,\text{eq}} = g_\chi \left( \frac{M_\chi^2}{2\pi^2} \right)^{3/2} e^{-x} \]

produced by the back-reaction \( ff' \rightarrow \chi \chi \) at a given temperature, where \( g_\chi \) is the spin degrees of freedom, \( T \) is the temperature and \( M_\chi \) is the mass of the relic. For particles which may potentially play the role of cold dark matter, the relevant temperature is order of \( \frac{M_\chi}{20} \) and the non-relativistic equilibrium abundance is well justified.

In terms of the dimensionless variables \( Y_\chi \equiv n_\chi / s \) where \( s \) is the total entropy density, and \( x \equiv \frac{M_\chi}{T} \) the boltzmann equation becomes

\[ \frac{dY_\chi}{dx} = -\frac{\lambda(x)}{x^2} [Y^2_\chi - Y^2_{\chi,\text{eq}}] \]  

(12)

where

\[ \lambda(x) \equiv \left( \frac{\pi}{40} \right)^{1/2} M_{\text{pl}} M_\chi \left( \frac{g_{ss}}{g_s} \right)^{1/2} \langle \sigma v \rangle(x) \]  

(13)

\[ Y_{\chi,\text{eq}} = \frac{45}{2\pi^2} \left( \frac{\pi}{8} \right)^{1/2} \frac{g_\chi g_{ss}}{M_{\chi}} x^{3/2} e^{-x} \]  

(14)

where \( g_s \) and \( g_{ss} \) are the effective degrees of freedom of the energy density and entropy density respectively. Here \( M_{\text{pl}} = 2.4 \times 10^{19} \text{ GeV} \) is the Planck mass and \( M_\chi \) is the mass of Dipolar Dark Matter (\( \chi \)).

In the case of Majorana fermions only non-identical fermions can annihilate (\( \chi_1 \bar{\chi}_2 \rightarrow f \bar{f} \)) through the dipole moment operator as only the transition dipole moments (\( \mathcal{D}_{12}, \mu_{12} \)) are non-zero. When the mass difference \( \delta \) between \( \chi_1 \) and \( \chi_2 \) is small, the cross section for Majorana annihilation process is identical to that of the Dirac fermions (with \( \mathcal{D}, \mu \) replaced with \( \mathcal{D}_{12}, \mu_{12} \)). The iDDM pairs annihilate to either photons or charged pairs through the diagrams shown in Fig:
FIG. 4: Annihilation diagram for dipolar dark matter (DDM) pair into fermion particle-antiparticle pair

Hence the total cross-section is \( \sigma_{\text{ann}} v = \sigma_{\chi\chi \to 2\gamma} v + \sigma_{f\bar{f} \to 2\gamma} v \). Here we will calculate the cosmological relic abundance \( \Omega_h^2 \) of the iDDM by assuming standard freeze-out of annihilations via the dipole coupling to \( \gamma \) and there is no \( \chi\bar{\chi} \) asymmetry. In the nonrelativistic limit, the thermal average annihilation cross section \( \langle \sigma v \rangle \) reduces to an average over a Maxwell-Boltzmann distribution function [15]:

\[
\langle \sigma v \rangle = \frac{x^{3/2}}{2\pi^{1/2}} \int_0^1 (\sigma v) v^2 e^{-x v^2} dv
\]  

(15)

The DM annihilation rate for magnetic dipolar interaction, with fermions as the annihilation products is given by [16]

\[
(\sigma v) = \frac{e^2 \mu^2}{4\pi}
\]  

(16)

However we find that the dominant contribution to relic density comes from the annihilation through magnetic dipole interaction into \( W^+W^- \) given by

\[
(\sigma v) = \frac{3e^2 \mu_{12}^2}{4\pi} \left( 6 - \frac{m_W^2}{m_\chi^2} \right)
\]  

(17)

The present day mass density of iDDM particles \( \chi \) is given by

\[
\Omega_{\text{DDM},0} h^2 \sim \frac{x_f \ 8.5 \times 10^{-11} \text{GeV}^{-2}}{\langle \sigma v \rangle}
\]  

(18)

where we take \( x_f = 20 \).

The observed value of CDM density from the seven year WMAP data is \( \Omega_{\text{CDM}} h^2 = 0.1123 \pm 0.0105 \) \( (3\sigma) \) [17] (where \( h \) is the Hubble parameter in units of 100 km/s/Mpc). The annihilation cross-section required to get this value of \( \Omega h^2 \) is \( 1.81 \times 10^{-26} \text{cm}^3\text{s}^{-1} \). To obtain this value of annihilation cross section in our model we choose a DM mass of 160 GeV which gives \( \mu = 3.8 \times 10^{-7} \mu_B \).
V. DIRECT DETECTION OF MIDM

In direct detection of DM one measures WIMPs scattering off target nuclei. The scattering can be assumed to be either elastic or inelastic. In the case of inelastic scattering, the process is $\chi_1 + N \rightarrow \chi_2 + N$ where $\chi_1$ and $\chi_2$ are two different mass eigenstates, and in general, there is a mass difference between $\chi_1$ and $\chi_2$, $\delta = m_2 - m_1$. Due to this mass difference, the minimum DM kinetic energy needed for the nucleon scattering becomes higher [18]. There is a minimal velocity required to produce recoil energy $E_R$ in such an inelastic scattering

$$v_{\text{min}} = \sqrt{\frac{1}{2m_N E_R} \left( \frac{m_N E_R}{\mu} + \delta \right)}$$

(19)

where $m_N$ is the mass of the target nucleus, $\mu$ is the reduced mass of the WIMP-nucleus system, and $\delta$ is the WIMP-mass splitting. Here we assume the WIMPs to have a Maxwellian velocity distribution as described in [19].

The differential cross section per unit energy transfer for elastic scattering by a magnetic dipole moment interaction is given by [12]

$$\frac{d\sigma}{dE_R} = \frac{e^2 \mu_N^2}{4\pi E_R} \left[ Z^2 \left( 1 - \frac{E_R}{2m_N v^2} - \frac{E_R}{m_{\chi} v^2} \right) + \frac{I + 1}{3I} \left( \frac{\mu_N}{\frac{e}{2m_p}} \right)^2 \frac{m_N E_R}{m_p^2 v^2} \right] |F(q)|^2$$

(20)

where the first term is due to interaction with the charge of the nucleus and the second term with the magnetic dipole moment of the nucleus. Here $I$ denotes the nuclear spin, $\mu_N$ and
\( \mu_\chi \) denote the magnetic moments of nucleus and DM respectively, \( Z \) is atomic number of the target nucleus and \( |F(q)|^2 \) is the nuclear form factor. Although the nuclear charge form factor and the nuclear magnetic moment form factor can be different we assume them to be approximately equal for simplicity [12]. The differential cross section given by 20 is used to calculate the event rate spectrum. We use the recently released modulation data from the COGENT experiment [4] as quoted in [20] and also the latest modulation data from DAMA [5]. The allowed parameter space extracted assuming magnetic dipolar interaction is shown in Fig. 6. It can be seen from the figure that DAMA and COGENT can both be explained for a small sliver of parameter space for a very small mass difference of about 4-5 keV. Also the bound from relic density is a much more stringent constraint compared to the direct detection bound from DAMA or COGENT.

\[ m_\chi = 160 \text{ GeV} \]

FIG. 6: Allowed parameter space in the \( M_\chi-\delta \) plane for COGENT and DAMA. Solid line represents bound from relic density.
VI. INDIRECT DETECTION OF MIDM

The recently reported excesses of positrons and antiprotons in cosmic rays by the experiments like PAMELA [6, 25, 26] and of electrons+ positrons by Fermi[7, 27, 28] can be explained by dark matter annihilation with possibly a boost factor required in the DM annihilation cross section. This boost factor is explained either by astrophysical sources or effects like Sommerfeld enhancement.

We fix the DM mass to be 160 GeV which gives the correct relic density for a DM annihilation cross section of \(1.81 \times 10^{-26}\) cm\(^3\)s\(^{-1}\). The dominant contribution to relic density comes from the \(W\) channel as shown in the previous section. But in order to obtain the positron and antiproton fluxes for the indirect detection analysis, we take contributions from \(W\) as well as the leptonic channels \(e, \mu, \text{ and } \tau\). In case of \(e\) the cross section will be a \(\delta\)-function.

The method followed here to obtain the positron and antiproton fluxes is outlined in [21]. We use [22] to obtain event spectra for positrons and antiprotons produced from \(l\bar{l}\) (\(l = e, \mu, \tau\)) and \(W^+W^-\). This is then fed into GALPROP [23, 24] which calculates the final fluxes of positrons and antiprotons to be compared with experiment. The diffusion parameters used in the Galprop code are as tabled in [21]. The DM annihilation cross section used for calculating the positron and antiproton fluxes is \(1.81 \times 10^{-25}\) cm\(^3\)s\(^{-1}\), a boost factor of 10 is required to fit the data. Our results are shown in Fig. 7, Fig. 8 and Fig. 9. The positron flux shows fairly good agreement with the PAMELA data [6] as seen in Fig. 8. The antiproton flux is also within the observed values as shown in Fig. 9 due to a relatively light DM mass of 160 GeV and a very small boost in the cross section.

VII. SUMMARY

We have consider a minimal extension of the standard model which can explain non-zero light neutrino mass, magnetic moment of heavy RH singlet neutrino which we consider here as a DM candidate. We have shown that the inelastic dipole dark matter particle (which is a heavy RH singlet fermion in this case) with non-zero electric and/ or magnetic dipole moment can satisfy the experimental and observational bounds. Furthermore, this scenario may be tested at future particle colliders (such as the Large Hadron Collider (LHC) ) or
FIG. 7: The \((e^- + e^+)\) flux for the 160 GeV DM compared with FERMI-LAT data \([27, 28]\). Dashed denotes the CR background and dotted line is the DM annihilation signal.

FIG. 8: Positron flux ratio for the 160 GeV DM compared with Pamela data \([6]\). The annihilation cross section is taken to be \(\sigma v_{rel} = 1.81 \times 10^{-25} cm^3 s^{-1}\) which corresponds to a boost of 10.

dark matter detection experiments.

At the same time, it gives the connection between neutrino mass and magnetic dipole coupling which has opened up new possibilities for model builders. We have considered the dipole moment interactions between the heavy-light and heavy-heavy neutrino counterparts. As a result, the large magnetic moments of heavy Majorana neutrinos can enhance the
FIG. 9: Antiproton/Proton flux ratio for the 160 GeV DM compared with Pamela data [25, 26]. The annihilation cross section is taken to be $\sigma v_{rel} = 1.81 \times 10^{-25} \text{cm}^3\text{s}^{-1}$ for all annihilation channels with a boost of 10.

production cross section of TeV scale right-handed neutrinos though the Drell-Yan process, $e^+e^- \rightarrow \gamma, Z^* \rightarrow N_iN_j \ (i \neq j)$, which is within the reach of the future linear collider (ILC).

The model also provides a good agreement with the indirect detection experiments like PAMELA and FERMI consistent with the relic density bound from WMAP. At the same time we also constrain magnetic dipole moment from Direct detection experiments like DAMA and COGENT. In our model we do not find a common parameter space for DAMA and COGENT using the annual modulation data from both experiments. We also find that the relic density constraint is much more stringent compared to constraints from DAMA and COGENT.

[1] P.F. Smith and J.R.J. Benett, Nucl. Phys. B149 (1979) 525; S. Walfram, Phys. Lett. B82 (1979) 65.
[2] A. Gould et al.: Phys. Lett. B 238, 337 (1990)
[3] S. Davidson, B. Campbell and D. Bailey, Phys. Rev.D43 (1991) 2314.
[4] C. E. Aalseth et al., “Search for an Annual Modulation in a P-type Point Contact Germanium
Dark arXiv:1106.0650 [astro-ph.CO].

[5] R. Bernabei et al. [DAMA Collaboration], Eur. Phys. J. C 56, 333 (2008) [arXiv:0804.2741 [astro-ph]].

[6] O. Adriani et al., arXiv:0810.4995 [astro-ph].

[7] A. A. Abdo et al. [The Fermi LAT Collaboration], arXiv:0905.0025 [astro-ph.HE]. Nature 456, 362 (2008).

[8] I. Cholis, L. Goodenough, D. Hooper, M. Simet and N. Weiner, arXiv:0809.1683 [hep-ph].

[9] P. Meade, M. Papucci, A. Strumia and T. Volansky, arXiv:0905.0480 [hep-ph].

[10] S. Chang, N. Weiner, and I. Yavin, Phys.Rev. D82, 125011 (2010), 1007.4200.

[11] A. L. Fitzpatrick, K. M. Zurek, Phys. Rev. D82, 075004 (2010). [arXiv:1007.5325 [hep-ph]].

[12] V. Barger, W. -Y. Keung, D. Marfatia, Phys. Lett. B696, 74-78 (2011). [arXiv:1007.4345 [hep-ph]].

[13] Marc Sher; Phys. Rev. Lett. 87 16 (2001).

[14] R. Escribano and E. Masso; Phys. Lett. B 395 369 (1997).

[15] P. Gondolo and G. Gelmini, Nucl. Phys. B360, 145 (1991).

[16] E. Masso, S. Mohanty, S. Rao, Phys. Rev. D80, 036009 (2009). [arXiv:0906.1979 [hep-ph]].

[17] E. Komatsu et al., arXiv:1001.4538 [astro-ph.CO].

[18] D. Tucker-Smith and N. Weiner, Phys. Rev. D 64, 043502 (2001) [arXiv:hep-ph/0101138];
D. Tucker-Smith and N. Weiner, Phys. Rev. D 72, 063509 (2005) [arXiv:hep-ph/0402065];
S. Chang, G. D. Kribs, D. Tucker-Smith and N. Weiner, arXiv:0807.2250 [hep-ph].

[19] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. 267 (1996) 195.

[20] M. T. Frandsen, F. Kahlhoefer, J. March-Russell, C. McCabe, M. McCullough and K. Schmidt-Hoberg, arXiv:1105.3734 [hep-ph].

[21] S. Mohanty, S. Rao, D. P. Roy, [arXiv:1009.5058 [hep-ph]].

[22] M. Cirelli, G. Corcella, A. Hektor, G. Hutsi, M. Kadastik, P. Panci, M. Raidal, F. Sala
et al., [arXiv:1012.4515 [hep-ph]]; P. Ciafaloni, D. Comelli, A. Riotto, F. Sala, A. Strumia,
A. Urbano, JCAP 1103 (2011) 019. [arXiv:1009.0224 [hep-ph]].

[23] I. V. Moskalenko and A. W. Strong, Astrophys. J. 493, 694 (1998) [arXiv:astro-ph/9710124].

[24] A. W. Strong, I. V. Moskalenko and V. S. Ptuskin, Ann. Rev. Nucl. Part. Sci. 57, 285 (2007)
[arXiv:astro-ph/0701517].

[25] O. Adriani et al., Phys. Rev. Lett. 102, 051101 (2009) [arXiv:0810.4994 [astro-ph]].
[26] O. Adriani et al. [PAMELA Collaboration], “PAMELA results on the cosmic-ray antiproton flux from 60 MeV to 180 GeV in kinetic energy,” arXiv:1007.0821 [astro-ph.HE].

[27] A. A. Abdo et al. [The Fermi LAT Collaboration], Phys. Rev. Lett. 102, 181101 (2009) [arXiv:0905.0025 [astro-ph.HE]].

[28] M. Ackermann et al. [The Fermi-LAT collaboration], “Fermi LAT observations of cosmic-ray electrons from 7 GeV to 1 TeV,” arXiv:1008.3999 [astro-ph.HE].