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Correlating neutrino magnetic moment and inert scalar dark matter in Type-III radiative scenario

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We discuss dark matter phenomenology, neutrino magnetic moment and their masses in a Type-III radiative scenario. The Standard Model is enriched with three vector-like fermion triplets and two inert scalar doublets to provide a suitable platform for the above phenomenological aspects. The inert scalars contribute to total relic density of dark matter in the Universe. Neutrino aspects are realised at one-loop with magnetic moment obtained through charged scalars, while neutrino mass gets contribution from charged and neutral scalars. Taking inert scalars up to 2 TeV and triplet fermion in few hundred TeV range, we obtain a common parameter space, compatible with experimental limits associated with both neutrino and dark matter sectors. Finally, we demonstrate that the model is able to provide neutrino magnetic moments in a wide range from $10^{-12}\mu_B$ to $10^{-10}\mu_B$, meeting the bounds of various experiments such as Super-K, TEXONO, Borexino and XENONnT.

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1. Introduction

The success of the Standard Model (SM) in explaining the observed phenomena in particle physics is indubitable. Yet, there are several exceptions, e.g., dark matter content of the universe, neutrino masses and mixing, baryon asymmetry of the Universe, etc. which cannot be realized within its realm. Hence, the exploration of physics beyond the standard model becomes inevitable for the understanding of several open problems of nature. To accommodate the non-zero neutrino mass, many new ideas are put forward, which are expected to have implications in many other sectors. One such possibility amongst them is that neutrinos can possess electromagnetic properties like electric and magnetic dipole moments. Solar, accelerator and reactor experiments possibly could provide the direct measurement of magnetic moments and eventually put the limits on them.

The nature and identity of dark matter remains still a mystery. Thus, we raise a question, whether a dark matter particle running in the loop, forming an electromagnetic vertex can provide neutrino magnetic moment. With this view point, we provide a simple model [1] that can accommodate non-zero magnetic moment for neutrino and also discuss dark matter phenomenology in a correlative manner.

2. Model description

To address the neutrino mass, magnetic moment and dark matter in a common platform, we extend the SM framework with three vector-like fermion triplets Σ_k, with $k = 1, 2, 3$ and two inert scalar doublets η_j, with $j = 1, 2$. We impose an additional Z_2 symmetry to realize neutrino phenomenology at one-loop and also for the stability of the dark matter candidate. The particle content along with their charges are displayed in Table. 1.

	Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Z_2
Leptons	$\ell_L = (\nu, e)_L^T$	$(\mathbf{1}, \mathbf{2}, -1/2)$	+
	e_R	$(\mathbf{1}, \mathbf{1}, -1)$	+
	$\Sigma_{k(L,R)}$	$(\mathbf{1}, \mathbf{3}, 0)$	−
Scalars	H	$(\mathbf{1}, \mathbf{2}, 1/2)$	+
	η_j	$(\mathbf{1}, \mathbf{2}, 1/2)$	−

Table 1: Fields and their charges in the present model.

The relevant Lagrangian term involving the new particles of the model is given by

$$\mathcal{L}_\Sigma = y'_{\alpha k}\overline{\ell_{\alpha L}}\Sigma_{kR}\tilde{\eta}_j + y_{\alpha k}\overline{\ell^c_{\alpha L}} i\sigma_2 \Sigma_{kL}\eta_j + \frac{i}{2}\mathrm{Tr}[\overline{\Sigma}\gamma^\mu D_\mu \Sigma] - \frac{1}{2}\mathrm{Tr}[\overline{\Sigma} M_\Sigma \Sigma] + \text{h.c.}\,, \quad (1)$$

where $\Sigma^{+,0} = \Sigma_L^{+,0} + \Sigma_R^{+,0}$ and $\Sigma = (\Sigma_1, \Sigma_2, \Sigma_3)^T$.

The Lagrangian for the scalar sector takes the form

$$\mathcal{L}_{\text{scalar}} = \left|\left(\partial_\mu + \frac{i}{2} g\,\sigma^a W_\mu^a + \frac{i}{2} g' B_\mu\right)\eta_1\right|^2 + \left|\left(\partial_\mu + \frac{i}{2} g\,\sigma^a W_\mu^a + \frac{i}{2} g' B_\mu\right)\eta_2\right|^2 - V(H, \eta_1, \eta_2),$$

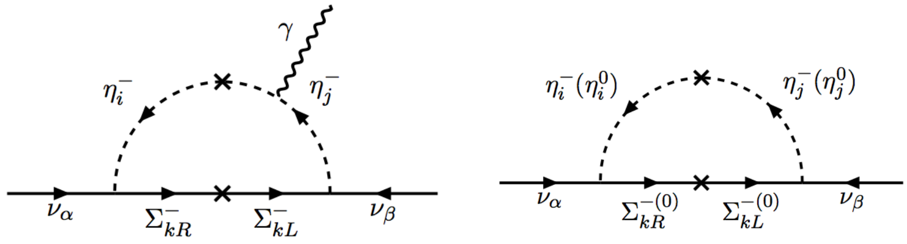


Figure 1: One-loop Feynman diagram for transition magnetic moment (left panel) and light neutrino mass (right panel).

where, the inert doublets are denoted by $\eta_j = \left(\eta_j^+, \eta_j^0\right)^T$, with $\eta_j^0 = (\eta_j^R + i\eta_j^I)/\sqrt{2}$. $V(H, \eta_1, \eta_2)$ represents the scalar potential, from which the mass matrices of the charged and neural scalar components can be obtained, and the diagonalization of the same yield the physical masses.

3. Neutrino Masses and Magnetic moment

Though neutrino is electrically neutral, it can have electromagnetic interaction at loop level. In the present model, the transition magnetic moment arises from one-loop diagram shown in the left panel of Fig. 1, and the expression of corresponding contribution takes the form [1]

$$(\mu_\nu)_{\alpha\beta} = \sum_{k=1}^{3} \frac{(Y^2)_{\alpha\beta}}{8\pi^2} M_{\Sigma_k^+} \left[\frac{(1+\sin 2\theta_C)}{M_{C2}^2} \left(\ln\left[\frac{M_{C2}^2}{M_{\Sigma_k^+}^2}\right] - 1 \right) + \frac{(1-\sin 2\theta_C)}{M_{C1}^2} \left(\ln\left[\frac{M_{C1}^2}{M_{\Sigma_k^+}^2}\right] - 1 \right) \right], \quad (2)$$

where $y = y' = Y$ and $(Y^2)_{\alpha\beta} = Y_{\alpha k} Y_{k\beta}^T$.

The contribution to neutrino mass can arise at one-loop from two diagrams, one with charged scalars and fermion triplet in the loop while the other with neutral scalars and fermion triplets. The relevant diagrams are provided in the right panel of Fig. 1 and the corresponding contribution takes the form [1]

$$\begin{aligned}(\mathcal{M}_\nu)_{\alpha\beta} = & \sum_{k=1}^{3} \frac{(Y^2)_{\alpha\beta}}{32\pi^2} M_{\Sigma_k^+} \left[\frac{(1+\sin 2\theta_C) M_{C2}^2}{M_{\Sigma_k^+}^2 - M_{C2}^2} \ln\left(\frac{M_{\Sigma_k^+}^2}{M_{C2}^2}\right) + \frac{(1-\sin 2\theta_C) M_{C1}^2}{M_{\Sigma_k^+}^2 - M_{C1}^2} \ln\left(\frac{M_{\Sigma_k^+}^2}{M_{C1}^2}\right) \right] \\ & + \sum_{k=1}^{3} \frac{(Y^2)_{\alpha\beta}}{32\pi^2} M_{\Sigma_k^0} \left[\frac{(1+\sin 2\theta_R) M_{R2}^2}{M_{\Sigma_k^0}^2 - M_{R2}^2} \ln\left(\frac{M_{\Sigma_k^0}^2}{M_{R2}^2}\right) + \frac{(1-\sin 2\theta_R) M_{R1}^2}{M_{\Sigma_k^0}^2 - M_{R1}^2} \ln\left(\frac{M_{\Sigma_k^0}^2}{M_{R1}^2}\right) \right] \\ & - \sum_{k=1}^{3} \frac{(Y^2)_{\alpha\beta}}{32\pi^2} M_{\Sigma_k^0} \left[\frac{(1+\sin 2\theta_I) M_{I2}^2}{M_{\Sigma_k^0}^2 - M_{I2}^2} \ln\left(\frac{M_{\Sigma_k^0}^2}{M_{I2}^2}\right) + \frac{(1-\sin 2\theta_I) M_{I1}^2}{M_{\Sigma_k^0}^2 - M_{I1}^2} \ln\left(\frac{M_{\Sigma_k^0}^2}{M_{I1}^2}\right) \right]. \end{aligned} \quad (3)$$

4. Dark Matter phenomenology

In our proposed model, we consider the new scalar particles as dark matter candidates and study their phenomenology up to 2 TeV mass range. All the inert scalar components contribute to the dark matter relic density of the Universe through annihilations and co-annihilations. With the scalar Higgs mediator, $\phi_i^R \phi_j^R$ can annihilate to $f\bar{f},\ W^+W^-, ZZ,\ hh$ and via Z boson, $\phi_i^R \phi_j^I$ can co-annihilate to $f\bar{f},\ W^+W^-,\ Zh$. Additionally, the charged and neutral components can co-annihilate to $f'\overline{f''}, AW^\pm, ZW^\pm, hW^\pm$ through $W^\pm$. Here, $f' = u, c, t, \nu_e, \nu_\mu, \nu_\tau$ and $f'' = d, s, b, e, \mu, \tau$. The abundance of dark matter can be computed using the standard formula,

$$\Omega h^2 = \frac{1.07 \times 10^9 \text{ GeV}^{-1}}{M_{\text{Pl}}\ {g_*}^{1/2}} \frac{1}{J(x_f)} \ , \tag{4}$$

where, $M_{\text{Pl}} = 1.22 \times 10^{19}$ GeV and $g_* = 106.75$ denote the Planck mass and total number of effective relativistic degrees of freedom respectively and the function $J(x_f)$ is related to the thermal-averaged WIMP pair annihilation cross section.

The direct search signals mainly come from the scattering off the scalar dark matter from the nucleus via the Higgs boson. Thus, the DM-nucleon cross section in Higgs portal can provide a spin-independent (SI) cross section, whose sensitivity can be checked with stringent upper bound of LZ-ZEPLIN experiment. The corresponding cross section is given by [2],

$$\sigma_{\text{SI}} = \frac{1}{4\pi} \left(\frac{M_n M_{R1}}{M_n + M_{R1}} \right)^2 \left(\frac{\lambda_{L1} \cos^2\theta_R + \lambda_{L2} \sin^2\theta_R}{2 M_{R1} M_h^2} \right)^2 f^2 M_n^2, \tag{5}$$

where, M_n denotes the nucleon mass, nucleonic matrix element $f \sim 0.3$. We have used micrOMEGAs to compute relic density and also DM-nucleon cross section.

5. Analysis

In the present framework, we consider ϕ_1^R to be the lightest inert scalar eigen state and there are five other heavier scalars. To make the analysis simpler, we consider the mass parameters related to the scalar masses as follows: one parameter M_{R1} corresponding to the mass of ϕ_1^R and three mass splittings namely δ, δ_{IR} and δ_{CR}. The masses of the rest of the inert scalars can be derived using the following relations:

$$M_{R2} - M_{R1} = M_{I2} - M_{I1} = M_{C2} - M_{C1} = \delta, \quad M_{Ri} - M_{Ii} = \delta_{\text{IR}}, \quad M_{Ri} - M_{Ci} = \delta_{\text{CR}} \ , \tag{6}$$

where, $i = 1, 2$. We have performed the scan over model parameters as given below, in order to obtain the region, consistent with experimental bounds associated with both dark matter and neutrino sectors:

$$\begin{aligned} &100 \text{ GeV} \le M_{R1} \le 2000 \text{ GeV}, \quad 0 \le \sin\theta_R \le 1, \\ &0.1 \text{ GeV} \le \delta < 200 \text{ GeV}, \quad 0.1 \text{ GeV} \le \delta_{\text{IR}}, \delta_{\text{CR}} \le 20 \text{ GeV}. \end{aligned} \tag{7}$$

We filter out the parameter space by providing Planck constraint on relic density [3] in 3σ and then compute DM-nucleon SI cross section for the available parameter space. We project the cross section as a function of M_{R1} in the left panel of Fig. 2 with cyan data points, where the dashed brown line corresponds to LZ-ZEPLIN upper limit [4]. Choosing a set of values for the Yukawa and fermion triplet mass, with the obtained parameter space, one can satisfy the aspects of neutrino mass and mixing phenomenology. The blue, green and red data points corresponding to 25, 80 and 420 TeV of triplet mass and suitable Yukawa satisfy the neutrino magnetic moment and light neutrino mass in the desired range simultaneously, as projected in the right panel. We notice that a wide region of dark matter mass is favoured as we move towards high scale (triplet mass) and moreover the favourable region shifts towards larger values with scale. Using two specific benchmark values

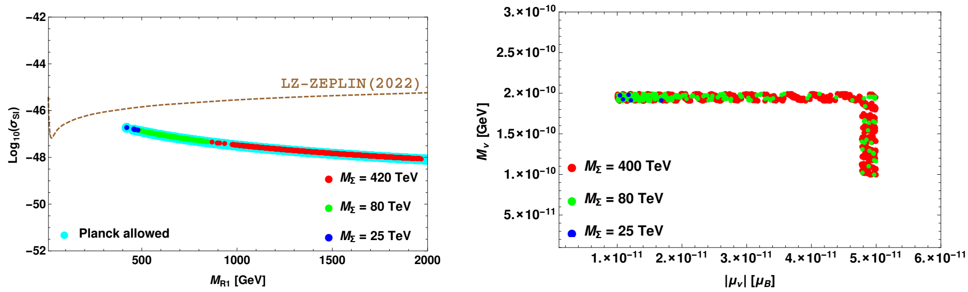


Figure 2: Left panel projects SI WIMP-nucleon cross section as a function M_{R1}, with dashed brown line of LZ-ZEPLIN upper limit [4]. Cyan data points satisfy Planck limit [3] on relic abundance in 3σ. Blue, green and red data points satisfy neutrino mass and magnetic moment for a specific set of values for fermion triplet and Yukawa, visible in the right panel.

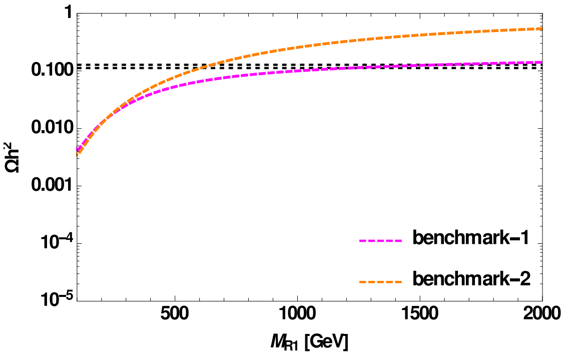
(shown as BM-1 and BM-2 in table 2) which are favourable to explain both neutrino and dark matter aspects discussed so far, we project relic abundance scalar dark matter in the left panel of Fig. 3. In the right panel of Fig. 3, we project neutrino magnetic moment as a function of dark matter mass, choosing specific set of values assigned to triplet fermion. It is transparent that the model parameters are able to provide neutrino magnetic moment in the range $10^{-12}\mu_B$ to $10^{-10}\mu_B$, sensitive to the upper limits from various experiments, e.g., Super-K, TEXONO, Borexino, XENON1T, XENONnT and white dwarfs (colored horizontal lines). Thus, from all the above discussions made, it is evident that this simple framework can provide a consistent phenomenological platform for a correlative study of neutrino magnetic moment (especially), mass and dark matter physics.

	M_{R1} [GeV]	δ [GeV]	$\delta_{\rm CR}$ [GeV]	$\delta_{\rm IR}$ [GeV]	M_Σ [TeV]	$\lvert\mu_\nu\rvert$ $[\mu_B]$	Ωh^2
BM-1	1472	101.69	9.03	0.35	420	2.73×10^{-11}	0.123
BM-2	628	36.40	4.38	3.45	80	3.03×10^{-11}	0.119

Table 2: Set of benchmarks from the consistent parameter space.

6. Conclusions

In this work, we have attempted to address neutrino mass, magnetic moment and dark matter phenomenology in a common framework. For this purpose, we have extended the standard model with three vector-like fermion triplets and two inert scalar doublets to realize Type-III radiative scenario. A pair of charged scalars help in obtaining neutrino magnetic moment, all charged and neutral scalars come up in getting light neutrino mass at one-loop level. All the inert scalars participate in annihilation and co-annihilation channels to provide total dark matter relic density



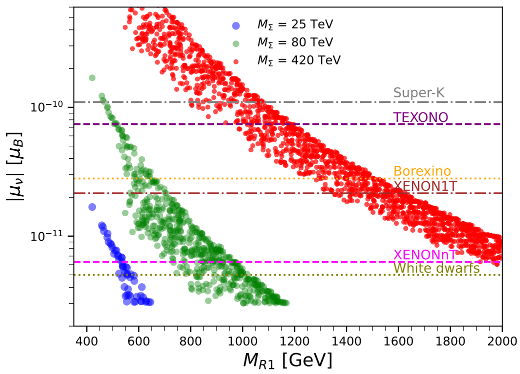


Figure 3: Left panel depicts the relic density as a function of dark matter mass for the chosen benchmark of the favourable parameter space of table-2. Right panel portrays the allowed region of neutrino magnetic moment with the mass spectrum of dark matter and fermion triplet. Horizontal colored lines stand for the upper bounds from different experiments.

of the Universe, consistent with Planck satellite data and also provide a suitable cross section with nucleon, sensitive to LZ-ZEPLIN upper limit. Finally, we have also demonstrated that the model is able to provide neutrino magnetic moment in a wide range ($10^{-12}\mu_B$ to $10^{-10}\mu_B$), in the same ball park of Borexino, Super-K, TEXONO, XENONnT and white dwarfs. Overall, this simple model provides a suitable platform to study neutrino phenomenology, especially the neutrino magnetic moment and also dark matter aspects.

Acknowledgments

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