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Neutrino masses, muon $g - 2$, dark matter, lithium problem, and leptogenesis at TeV-scale

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ABSTRACT

Observational evidences of nonzero neutrino masses and the existence of dark matter request physics beyond Standard Model. A model with extra scalars and vector-like leptonic fermions is introduced. By imposing a Z_2 symmetry, the neutrino masses as well as anomalous muon magnetic moment can be generated via one-loop effects at TeV-scale. An effort of explaining dark matter and lithium problem is presented. However, we found the leptogenesis produced is too small in this model.

1. Introduction

There are some solid evidences for the physics beyond the Standard Model (SM) of particle physics. One is the observation of neutrino oscillations which has established that neutrinos have very small masses. The low energy accelerator experiment of the muon anomalous magnetic moment also gives another hint for the physics beyond the SM. Besides that there are also evidences from early Universe cosmology and astronomy: the existence of dark matter and matter–antimatter asymmetry of the Universe [1]. The observed baryon asymmetry of the Universe cannot be explained within the SM with one CP violating phase.

Standard Big Bang Nucleosynthesis (SBBN) is one of the most reliable and farthest reaching probes of early Universe cosmology. One can calculate the relative abundances of light elements to hydrogen (H) at the end of the "first three minutes" after the Big Bang. Despite the great success of SBBN, it has been noted that the prediction for the ratio of ^{7}Li/H and the isotopic ratio ^{6}Li/^{7}Li do not agree with current observations, called the "lithium problems" [2]. The SBBN model predicts primordial ^{6}Li abundance about three orders of magnitude smaller than the observed abundance level and ^{7}Li abundance a factor of two to three larger when one adopts a value of the energy density of baryon inferred from the WMAP data. They do not have an astrophysical solution in a complete manner at present. One of the plausible solutions is the existence of primordial late-decaying charged particles in the early Universe (CBBN) [3].

In this Letter, we consider a model which provides the possibility to address all these issues within a single framework. Our model is an extension of the radiative seesaw mechanism [4], in which an additional scalar doublet and Majorana right-handed neutrinos are introduced and are assigned to be odd under the new discrete symmetry Z_2. Since the Z_2 is an exact symmetry the lightest Z_2-odd particle can be the candidate of dark matter and the neutrino masses are generated at one-loop level with the canonical seesaw structure but suppressed by the loop factors. We consider the SM particle plus extra scalars and vector-like leptonic fermions. By imposing a Z_2 symmetry, all the new particles can only appear in pairs through the loops due to the Z_2-odd parity assignment. The neutrino masses can be generated via one-loop effects at the TeV-scale, in addition to the loop suppression factor the tiny neutrino mass scale is controlled by the mixing between charged scalars in our scenario. Similar mechanism will also contribute to muon anomalous magnetic moment which is easily fitted into the current deviation between the experimental data and SM prediction. The lightest neutral Z_2-odd particle provides the dark matter candidate in our model. The model also contains a long-lived charged particle requested by the scenario

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Table 1
The content of the model.

Field	l_L	l_R	ϕ_1	Ψ'	Σ'	ϕ_2	S
SM	$(2,-1)$	$(1,-2)$	$(2,-1)$	$(2,-1)$	$(1,-2)$	$(2,-1)$	$(1,2)$
Z_2	$+$	$+$	$+$	$-$	$-$	$-$	$-$

of CBBN where the long lifetime is due to the small mixing between charged scalars and phase space suppression of the three body decay. Finally, the possibility of low-scale leptogenesis can be achieved if the hierarchical Yukawa couplings among the new particles are satisfied.

2. The model

In order to address the above-mentioned issues, we introduced a set of vector-like leptons (Ψ', Σ'), an inert doublet Higgs (ϕ_2), and a singly charged scalar (S) in our model. A discrete symmetry Z_2 is imposed such that all the new particles are odd and the SM particles are even under this parity projection. Ψ' and Σ' carry the same quantum number as left- and right-handed leptons in SM. According to the vector structure of these fermions, our model is anomaly free and their mass terms can be realized as

$$L_{mass} = M_1' \bar{\Psi}' \Psi' + M_2' \bar{\Sigma}' \Sigma'. \tag{1}$$

The particle contents of the model are shown in Table 1 (where we've neglected the quark sector). The transformations under the SM gauge group are shown explicitly where the first one in the parenthesis is for the $SU(2)$ and the second one is for the $U(1)_Y$.

Note that the scalar ϕ_1 corresponds to the SM Higgs doublet and l_L, l_R denote SM leptons. Except the Z_2 charge, the new leptons and inert Higgs transform in the same way as the SM leptons and Higgs, so we have the following new Yukawa interacting terms

$$\begin{aligned} L_Y &= f_{\alpha i} l_{L\alpha}^T C^{-1} \Psi'_{Li} S^+ + y_{\alpha i} \bar{\Psi}'_{Li} \tilde{\phi}_2 l_{R\alpha} \\ &\quad + g_{\alpha i} \bar{l}_{L\alpha} \tilde{\phi}_2 \Sigma'^-_{Ri} + h_{ij} \bar{\Psi}'_{Li} \tilde{\phi}_1 \Sigma'^-_{Rj} + \text{h.c.} \\ &= \big[f_{\alpha i} \big(\bar{\nu}_\alpha \Psi_i'^- + l_\alpha^- \bar{\Psi}_i'^{0c} \big) \big] S^+ \\ &\quad + y_{\alpha i} \big[\bar{\Psi}_i'^0 \phi_2^+ l_{R\alpha}^- - \Psi_i'^+ \phi_2^{0*} l_{R\alpha}^- \big] \\ &\quad + g_{\alpha i} \big[\bar{\nu}_\alpha \phi_2^+ \Sigma_{Ri}'^- - \bar{l}_\alpha \phi_2^{0*} \Sigma_{Ri}'^- \big] \\ &\quad + h_{ij} \big[\bar{\Psi}_{Li}'^0 \phi_1^+ \Sigma_{Rj}'^- - \Psi_{Li}'^+ \phi_1^{0*} \Sigma_{Rj}'^- \big] + \text{h.c.}, \end{aligned} \tag{2}$$

where α runs as e, μ, τ, and i stands for the number of new leptonic sectors, we need at least two sets of Ψ field in order to achieve successful leptogenesis which we leave the discussion in Section 2.5.

The scalar potential is given by

$$\begin{aligned} V(\phi_1, \phi_2, S^-) &= -\mu_1^2 |\phi_1|^2 + \lambda_1 |\phi_1|^4 + m_2^2 |\phi_2|^2 + \lambda_2 |\phi_2|^4 \\ &\quad + \lambda_3 |\phi_1|^2 |\phi_2|^2 + \lambda_4 |\phi_1^\dagger \phi_2|^2 \\ &\quad + \frac{\lambda_5}{2} \big[(\phi_1^\dagger \phi_2)^2 + \text{h.c.} \big] + m_s^2 |S|^2 + \lambda_s |S|^4 \\ &\quad + \mu \big[(\phi_1^{0*} \phi_2^- - \phi_1^- \phi_2^0) S^+ + \text{h.c.} \big]. \end{aligned} \tag{3}$$

We assume that the Z_2 symmetry is exactly conserved such that ϕ_2^0, the neutrino component of the field ϕ_2, will not generate the vacuum expectation value (VEV), that is, the symmetry breaking pattern is through $\langle \phi_1^0 \rangle = v$. We take $\phi_1^0 = \frac{v+h}{\sqrt{2}}$ where h is the SM Higgs scalar while the pseudoscalar and charged components of ϕ_1 become the longitudinal modes of Z and W bosons respectively. In the unitary gauge, these fields are gauged away, the cubic and quartic couplings of the potential can be written as

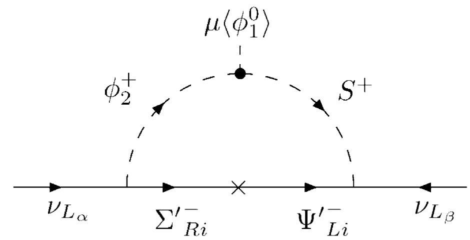

Fig. 1. 1-loop diagram for neutrino mass with new lepton in flavor eigenstate.

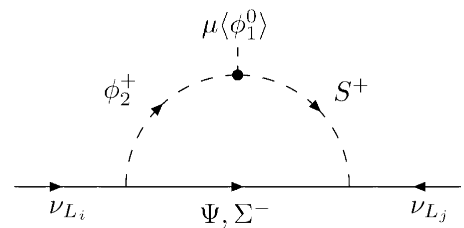

Fig. 2. 1-loop diagram for neutrino mass with new lepton in mass eigenstate.

$$\begin{aligned} V_{3,4} &= \lambda_1 v h^3 + \frac{\lambda_1}{4} h^4 + \lambda_2 |\phi_2|^4 + \lambda_3 v h |\phi_2|^2 + \frac{\lambda_3}{2} h^2 |\phi_2|^2 \\ &\quad + \lambda_4 v h |\phi_2^0|^2 + \frac{\lambda_4}{2} h^2 |\phi_2^0|^2 + \lambda_5 v h \big({\phi_{2R}^0}^2 - {\phi_{2I}^0}^2 \big) \\ &\quad + \frac{\lambda_5}{2} h^2 \big({\phi_{2R}^0}^2 - {\phi_{2I}^0}^2 \big) + \lambda_s |S|^4 + \Big[\frac{\mu}{2} h \phi_2^- S^+ + \text{h.c.} \Big], \end{aligned} \tag{4}$$

where $\phi_2 = (\phi_2^0, \phi_2^-)^T$ and $\phi_2^0 = \phi_{2R}^0 + i\phi_{2I}^0$ have been used. The mixing matrix between $S^\pm$ and $\phi_2^\pm$ is

$$\begin{pmatrix} \phi_2^+ & S^+ \end{pmatrix} \begin{pmatrix} m_2^2 + \frac{\lambda_3 v^2}{2} & \frac{\mu v}{\sqrt{2}} \\ \frac{\mu v}{\sqrt{2}} & m_s^2 \end{pmatrix} \begin{pmatrix} \phi_2^- \\ S^- \end{pmatrix}. \tag{5}$$

If we denote the mass eigenstates of the charged scalars by (P_1^-, P_2^-), then

$$\begin{pmatrix} P_1^- \\ P_2^- \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} \phi_2^- \\ S^- \end{pmatrix}, \tag{6}$$

and

$$\tan 2\delta = \frac{\sqrt{2}\mu v}{m_2^2 + \lambda_3 v^2/2 - m_s^2}. \tag{7}$$

For the fermionic sector the SM Higgs also contributes to the new leptons through the last term of Eq. (2) which mixes up the charged components as

$$\begin{pmatrix} \Psi_L'^- & \Sigma_L'^- \end{pmatrix} \begin{pmatrix} M'_1 & h\frac{v}{\sqrt{2}} \\ h\frac{v}{\sqrt{2}} & M'_2 \end{pmatrix} \begin{pmatrix} \Psi_R'^+ \\ \Sigma_R'^+ \end{pmatrix}. \tag{8}$$

Similarly, we have the rotating matrix between the flavor and mass eigenstates of charged components in our new leptons,

$$\begin{pmatrix} \Psi' \\ \Sigma' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \Psi \\ \Sigma \end{pmatrix}, \tag{9}$$

with eigenmasses M_1 and M_2 to Ψ and Σ respectively.

2.1. Neutrino mass generation

The neutrino masses in this model can be generated at one-loop level as shown in Figs. 1 and 2. As noticed above, the mixing

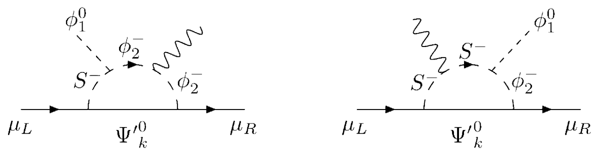

Fig. 3. Muon $g-2$ contributions from singly charged scalars mixing.

between two charged scalars $S^{\pm}$ and $\phi_2^{\pm}$ in the loop violates lepton number and is associated with a GIM cancelation that makes the corrections finite.

The generated neutrino mass matrix is

$$(m_\nu)_{\alpha\beta} = -if_{\alpha k}g_{\beta k}\sin\theta\cos\theta\sum_i M_i\mu\langle\phi_1^0\rangle \times\int\frac{d^4q}{(2\pi)^4}\frac{1}{(q^2-M_S^2)}\frac{1}{(q^2-M_{\phi_2}^2)}\frac{1}{(q^2-M_i^2)} = \frac{f_{\alpha k}g_{\beta k}\sin\theta\cos\theta\mu v}{16\sqrt{2}\pi^2}\big[F(M_1)-F(M_2)\big], \tag{10}$$

where the function F is

$$F(M) = \frac{M}{(M^2-M_{\phi_2}^2)} \times\left[\frac{M^2}{(M^2-M_S^2)}\ln\frac{M^2}{M_S^2}-\frac{M_{\phi_2}^2}{(M_{\phi_2}^2-M_S^2)}\ln\frac{M_{\phi_2}^2}{M_S^2}\right]. \tag{11}$$

This mass matrix contains both the loop suppression factor and the mass suppression factor hence it has similar structure as the radiative seesaw models [4]. Under the assumption that the masses of the new particles are as $M_i \gtrsim M_s \gtrsim M_{\phi_2^-}$ and taking $\sin\theta\cos\theta \sim \mathcal{O}(1)$, the neutrino masses can be approximated as

$$(m_\nu)_{\alpha\beta} \approx \frac{f_{\alpha k}g_{\beta k}}{16\sqrt{2}\pi^2}\frac{\mu v}{M_i} \approx 10^{-3}f_{\alpha i}g_{\beta i}\mu, \tag{12}$$

here we have taken $M_i \sim \mathcal{O}(1)$ TeV. If we let $(m_\nu)_{\alpha\beta} \sim 10^{-2}$ eV, then we obtain $f_{\alpha k}g_{\beta k}(\mu/\text{GeV}) \sim 10^{-8}$. We will come back to determine the size of these couplings and the scale μ when we address other issues later in this Letter.

2.2. Muon anomalous magnetic moment

The current limit of the muon anomalous magnetic moment is [2]

$$\Delta a_\mu = (290\pm 90)\times 10^{-11}, \tag{13}$$

which is 3.2σ deviation between SM calculations and experiment and hence opens a window to investigate physics beyond SM. The contributions to muon $g-2$ in our model are shown in Figs. 3 and 4. First, let's calculate the contributions to muon anomalous magnetic moment from Fig. 3. The result is

$$\Delta a^{NP}_{\mu(N_k)} = -\frac{\sin\delta\cos\delta}{16\pi^2}(f_{\mu k}y_{\mu k})\frac{m_\mu}{M_k}\big[F(x_{P_1})-F(x_{P_2})\big] \approx -\sin\delta\cos\delta(f_{\mu k}y_{\mu k})\times 10^{-5\sim -6}, \tag{14}$$

where $x_{P_i} = m^2_{P_i}/M_k^2$ and P_i are the mass eigenstates of the charged scalars. The function $F(x)$ is defined as

$$F(x) = \frac{1}{(1-x)^3}\big[1-x^2+2x\ln x\big], \tag{15}$$

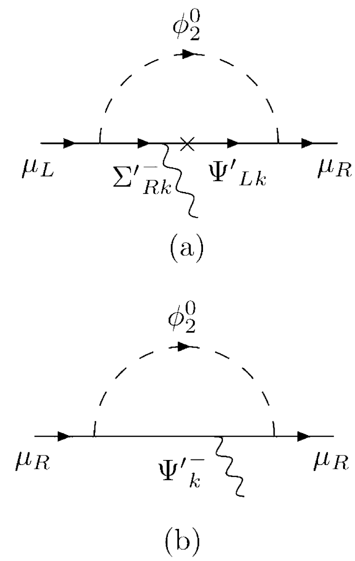

Fig. 4. Muon $g-2$ contributions from heavy charged leptons.

and the mixing angle satisfies the relation

$$\sin\delta\cos\delta = \frac{\mu v}{\sqrt{2}(m^2_{P_1}-m^2_{P_2})}. \tag{16}$$

A similar discussion can also be found in [5]. One should note that the contributions from the diagrams corresponding to those of Fig. 3 but without heavy Ψ' mass insertion are expected to have the same order of Eq. (14). It is because there is no small mixing suppression factor in those diagrams too. The contribution to the magnetic moment from Fig. 4(a) is

$$\Delta a^{NP}_{\mu(\Psi'^-_k,(a))} = \frac{g_{\mu k}y_{\mu k}\sin\theta\cos\theta}{12\pi^2}\frac{m_\mu}{M_k}G(x_{\phi_2^0}) \approx g_{\mu k}y_{\mu k}\times 10^{-5}, \tag{17}$$

where function $G(x)$ is

$$G(x) = -\frac{3}{2(1-x)^3}\big[3-4x+x^2+2\ln x\big] \tag{18}$$

and $x_{\phi_2^0} = M_k^2/m^2_{\phi_2^0}$. Finally the contribution to muon $g-2$ from Fig. 4(b) is

$$\Delta a^{NP}_{\mu(\Psi'^-_k,(b))} \approx \frac{y^2_{\mu k}}{48\pi^2}\frac{m^2_\mu}{M^2_{\phi_2^0}} \approx y^2_{\mu k}\times 10^{-11}, \tag{19}$$

where we have already put in $M_{\phi_2} \sim 500$ GeV which is from the constraint of dark matter relic abundance. In the above expressions we have already used $M_i \gtrsim M_{\phi_2^0} \gg m_\mu$. Note that there is an enhancement by the chirality flip in the internal fermion line in Figs. 3 and 4(a) which could explain the deviation of muon magnetic moment between SM prediction and experiment. The contribution from Eq. (19) is expected to be too small unless the couplings $y_{\mu k}$ are of order of $\mathcal{O}(10)$.

2.3. Dark matter

The neutral component of inert doublet (ID) ϕ_2, ϕ_2^0, can be identified as the dark matter (DM) candidate. The masses of ϕ^0_{2R} and ϕ^0_{2I} are given from the potential,

$$m^2_{\phi_{2(R,I)}} = \frac{m_2^2}{2}+\frac{1}{2}(\lambda_3+\lambda_4\pm\lambda_5)v^2. \tag{20}$$

The lightest Z_2-odd particle is determined by the sign of quartic coupling λ_5 which is related to the mass difference between scalar or pseudoscalar particles. However, the size of λ_5 is bounded by the elastic spin independent scattering between ϕ_2^0 and the nuclei with exchange of a Z boson. The cross-section of this process leads to about 3 orders of magnitudes above the current experimental limit [6,7]. In order to suppress this process kinematically, the mass difference between ϕ_{2R}^0 and ϕ_{2I}^0 should be at least of the order of few 100 keV. Its implications on dark matter detection and collider phenomenology will be discussion in Section 2.6.

If the DM arises as a thermal relic in the early Universe, its present density can be calculated by solving the Boltzmann equations which describe the evolution of the ϕ_2^0 abundance. The mass of the DM can then be determined from the relic abundance.

The currently most accurate determination of Ω_{CDM} comes from the global fits of cosmological parameters to a variety of observations. One finds [2]

$$\Omega_{CDM}h^2 = 0.106 \pm 0.008, \tag{21}$$

where h is the Hubble constant in unit of 100 km/(s Mpc). Numerically a WIMP (weakly interacting massive particle) will freeze out at temperature $T_f \sim m_{\phi_2^0}/25$ and the relation of the final abundance and the (co)annihilations rate can be well approximated by [8]

$$\Omega_{\phi_2^0}h^2 \approx \frac{3\times 10^{-27}\ \mathrm{cm^3\ s^{-1}}}{\langle \sigma_{ijA} v_{ij}\rangle}. \tag{22}$$

The relative velocity v_{ij} can be written as

$$v_{ij} = \frac{\sqrt{(p_i\cdot p_j)^2 - m_i^2 m_j^2}}{E_i E_j} \tag{23}$$

with p_i and E_i being the four-momentum and energy of particle i. In the non-relativistic limit of the center-of-mass frame, the v_{ij} can be simplified as

$$v_{ij} \approx 2\Lambda^{1/2}\left(1, m_i^2/s, m_j^2/s\right), \tag{24}$$

where $\Lambda(1, m_i^2/s, m_j^2/s) = (1 - m_i^2/s - m_j^2/s)^2 - 4(m_i^2/s)(m_j^2/s)$. During the freeze-out temperature we can approximate the relative velocity $v_{ij} \approx 0.3$. The dominant annihilation channel of DM is annihilation into SM gauge bosons, $\phi_2^0\phi_2^0 \to AA$, which gives [9]

$$\langle \sigma_A v\rangle \simeq \frac{3g_2^4 + g_Y^4 + 6g_2^2 g_Y^2}{256\pi M_{\phi_2^0}^2}. \tag{25}$$

While the trilinear and quartic couplings of the scalars in Eq. (4) also open the channels that DM can (co)annihilate into or through SM Higgs, the cross-sections can be written as [10]

$$\sigma_\lambda^{ij} = \frac{\lambda^{ij}}{32\pi m_{\phi_2^0}^2}, \tag{26}$$

where $\{i, j = 0, 1, 2, 3, 4\}$ stands for $\{\phi_{2R}^0, \phi_{2I}^0, \phi_2^+, \phi_2^-, S^\pm\}$, and the coefficients λ^{ij} are the combinations of quartic couplings given by

$$\begin{aligned}
&\lambda^{00} = \lambda^{11} = \frac{5}{2}\lambda_3^2 + 2\lambda_4^2 + 4\lambda_3\lambda_4 + 2\lambda_5^2,\\
&\lambda^{22} = \lambda^{33} = 2\lambda^{01} = 8\lambda_5^2,\\
&\lambda^{02} = \lambda^{03} = \lambda^{12} = \lambda^{13} = 2(\lambda_3/2 + \lambda_4)^2 + 2\lambda_5^2,\\
&\lambda^{23} = 4(\lambda_3 + \lambda_4)^2 + \lambda_3^2,\\
&\lambda^{24} = \lambda^{34} = 4(\lambda_3 + \lambda_4)^2 + (\mu/v)^2.
\end{aligned} \tag{27}$$

Here we expect the scale μ to be small as compared with v since it is related to neutrino masses as showed in Eq. (12). More detailed discussions of the inert doublet DM can be found in, according to different regimes, low-mass ($m_{\phi_2^0} \ll m_W$) [11], middle-mass ($m_{\phi_2^0} \lesssim m_W$) [12], and high-mass ($m_{\phi_2^0} \gg m_W$) [10] respectively. In our scenario we consider the high-mass DM regime ($m_{\phi_2^0} \gg m_W$), one can obtain the lower bound of $m_{\phi_2^0}$ by assuming all the quartic couplings $\lambda' s$ be smaller than the gauge couplings $g' s$. In the limit of $\lambda' s \to 0$, that is, the gauge-mediated processes are dominant we obtain the mass lower bound of DM to be

$$m_{\phi_2^0} \gtrsim 530\ \mathrm{GeV}. \tag{28}$$

2.4. Lithium problem

The lithium problem arises from the significant discrepancy between the primordial ^{6}Li and ^{7}Li abundance as predicted by Standard Big Bang Nucleosynthesis (SBBN), the WMAP baryon density, and the pre-Galactic lithium abundance inferred from observations of metal-poor stars [2,13]. The SBBN model predicts primordial ^{6}Li abundance about three orders of magnitude smaller than the observed abundance level and ^{7}Li abundance a factor of two to three larger when one adopts a value of the energy density of baryon inferred from the WMAP data.

One of the solutions to this is the so-called Catalytic Big Bang Nucleosynthesis (CBBN) [3] which states if a long-lived negatively-charged particle exists, it would form an exotic atom and work as a catalyzer. The bound state will induce reactions that can produce suitable primordial abundance of ^{6}Li and ^{7}Li. In our model the scalar singlet S^- will form the desired bound state with ^{4}He and this bound state will play the role as the catalyzer. The catalytic path to ^{6}Li and ^{9}Be is

$$\begin{aligned}
&S^- \to \left(^4\mathrm{He}S^-\right) \to {}^6\mathrm{Li} \quad \text{and}\\
&S^- \to \left(^4\mathrm{He}S^-\right) \to \left(^8\mathrm{Be}S^-\right) \to {}^8\mathrm{Be}.
\end{aligned} \tag{29}$$

And the key for the nuclear catalysis is an enormous enhancement of the reaction rates in the photonless recoil reactions mediated by S^-:

$$\begin{aligned}
&\left(^4\mathrm{He}S^-\right) + D \to {}^6\mathrm{Li} + S^- \quad \text{and}\\
&\left(^8\mathrm{Be}S^-\right) + n \to {}^9\mathrm{Be} + S^-.
\end{aligned} \tag{30}$$

The rates of these catalyzed reactions depend sensitively on the abundance of S^- at the relevant moments. The observations impose strong constraints on the lifetime of the negative charged particle to be $\sim 10^3$ s to live long enough to form the exotic atom and catalyze the reactions. In our model a long-lived S^- can be achieved through the three body decays into the lepton sectors and dark matter in the final states as shown in Fig. 4.

With the heavy mirror leptonic doublet in the intermediate states plus the small Yukawa couplings and the phase space suppression of the mass differences between S^- and ϕ_2, the long-lived S^- can be easily realized within our model. The decay rate of S^- in Figs. 5(a) and 5(b) are

$$\begin{aligned}
\Gamma_S|_{\alpha\beta(N_i)} &\approx \frac{(f_{\alpha i} y_{i\beta})^2}{30\pi^3 M_i^4} \times (\delta m)^5\left(1 - \frac{5m_l^2}{\delta m^2}\right)\\
&\approx f_{\alpha i}^2 y_{i\beta}^2 \times 10^{-15}\left(\frac{\delta m}{\mathrm{GeV}}\right)^5\ \mathrm{GeV},
\end{aligned} \tag{31}$$

where $\delta m = M_s - M_{\phi_2}$. The lifetime will be around

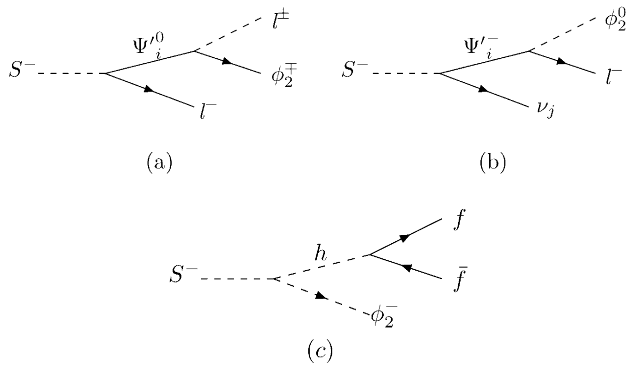

Fig. 5. Three body decays of S^-.

$$\tau_{\alpha\beta} \approx 6.6 \times f_{\alpha i}^{-2} y_{i\beta}^{-2} \times \left(\frac{\delta m}{\mathrm{GeV}}\right)^{-5} \times 10^{-10}\ \mathrm{s}, \tag{32}$$

thus we have the constraint

$$f_{\alpha i}^2 y_{\beta i}^2 \approx 10^{-12} \times \left(\frac{\delta m}{\mathrm{GeV}}\right)^{-5}. \tag{33}$$

Fig. 5(c) gives

$$\Gamma_{s(h)} = \frac{10^{-6}\mu^2}{4 \times 96(2\pi)^3} \frac{m_s}{m_h^4} (\delta m)^2$$
$$\approx 10^{-16} \times \left(\frac{\mu}{\mathrm{GeV}}\right)^2 \left(\frac{\delta m}{\mathrm{GeV}}\right)^2 \mathrm{GeV}, \tag{34}$$

and from that we obtain

$$\left(\frac{\mu}{\mathrm{GeV}}\right)^2 \left(\frac{\delta m}{\mathrm{GeV}}\right)^2 \approx 10^{-11}. \tag{35}$$

If we put the constraints from neutrino mass generation Eqs. (12), muon magnetic moment Eqs. (14) and (17), lithium problem Eqs. (33) and (35) altogether:

$$fg\left(\frac{\mu}{\mathrm{GeV}}\right) \sim 10^{-8},$$
$$\sin\delta\cos\delta(fy) < 10^{-5},$$
$$gy \sim 10^{-5},$$
$$f^2 y^2 \left(\frac{\delta m}{\mathrm{GeV}}\right)^5 \sim 10^{-12},$$
$$\left(\frac{\mu}{\mathrm{GeV}}\right)^2 \left(\frac{\delta m}{\mathrm{GeV}}\right)^2 \sim 10^{-11},$$

we find that all the above constraints can be satisfied simultaneously when

$$\mu \sim 10^{-5}\ \mathrm{GeV}, \qquad \delta m \lesssim 1\ \mathrm{GeV},$$
$$f \sim 10^{-1}, \qquad y \sim 10^{-3}, \quad \text{and} \quad g \sim 10^{-2}. \tag{36}$$

Here the small scale of μ will make the mixing in Eq. (16) small, that is, the contributions to muon $g-2$ from Fig. 3 are negligible. Therefore, the anomalous muon magnetic moment is mainly from Eq. (17). We should point out that these solutions are obtained under the assumption that the masses of the new particles are at TeV-scale. Note that these solutions are nontrivial in the sense that if one chose the scale of the new particles to be higher than $\mathcal{O}(10)$ TeV instead of $\mathcal{O}(1)$ TeV, the Yukawa couplings would be too large to alter the Higgs triviality bound.

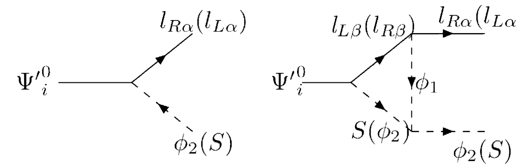

Fig. 6. Right-handed (left-handed) sector leptogenesis of Dirac type Ψ'^0 in our model.

2.5. Leptogenesis

One may also consider the possibility of leptogenesis in this model. Since there is no lepton number violation by heavy Majorana masses, the canonical leptogenesis does not exist in this scenario. However, the necessary ingredients, lepton number as well as CP violations, of leptogenesis occur as the coexistence of the Yukawa interactions and Higgs potential showed in Eqs. (2) and (3). We have the diagrams contributing to the asymmetry from the $\Psi_i'^0$ decay at one-loop order (Fig. 6). The CP asymmetry of the right-handed leptonic decay mode is given by

$$\epsilon_{\Psi_i'^0} = \frac{\Gamma(\Psi_i'^0 \to l_{R\alpha}\phi_2) - \Gamma(\bar{\Psi}_i'^0 \to \bar{l}_{R\alpha}\bar{\phi}_2)}{\Gamma(\Psi_i'^0 \to l_{R\alpha}\phi_2) + \Gamma(\bar{\Psi}_i'^0 \to \bar{l}_{R\alpha}\bar{\phi}_2)}$$
$$= -\sum_\beta \frac{1}{8\pi^2}\left(\frac{\mu m_{l_\beta}}{m_{\phi_1}^2}\right)\frac{\mathrm{Im}(y_{i\alpha}\lambda_{\alpha\beta} f_{i\beta})}{\sum_\alpha |y_{i\alpha}|^2}, \tag{37}$$

where m_{l_β} represents the SM charged lepton masses and $\lambda_{\alpha\beta}$ are the SM-like Yukawa couplings defined as $\lambda_{\alpha\beta}\bar{l}_{L\alpha}\phi_1 l_{R\beta}$. As we inherit the discussion of TeV-scale physics from previous sections, the same set parameters in Eq. (36) and $m_{l_\beta} = m_\tau$, $\lambda_{\alpha\beta} \approx \mathcal{O}(10^{-2})$ are used. Combining the result of baryon asymmetry converted from leptogenesis,

$$\frac{n_B}{s} = -\frac{28}{79}\frac{n_L}{s} = -1.36 \times 10^{-3}\epsilon_{\Psi_i'^0}\eta = 9 \times 10^{-11}, \tag{38}$$

where η is the efficiency factor. We found the amount of CP asymmetry as $\epsilon_{\Psi_i'^0} = \frac{1}{8\pi^2} \times 10^{-11}$ which is too small to explain the baryon asymmetry of our Universe even we take $\eta = 1$. For the result of the left-handed decaying mode showed in Fig. 6 we simply exchange the couplings f and y in Eq. (37), it turns out that the CP asymmetry is four orders of magnitudes smaller than the one of right-handed decays. The results are expected as the general features of the TeV-scale leptogenesis where the out-of-equilibrium condition on the decay width together with inducing a large enough CP asymmetry are both constrained by the smallness of neutrino masses unless some enhancement mechanisms are introduced [14].

2.6. Direct detection and collider phenomenology

Direct detection of DM can be measured through the elastic scattering of a DM particle with a nuclei inside the detector. The Z boson exchange channel constrains the lower bound of the mass splitting ($M_{\phi_{2R}^0} - M_{\phi_{2I}^0}$) to be of order a few 100 keV [6]. The cross-section of the processes through exchange a Higgs scalar h at tree level and gauge bosons at one-loop level are

$$\sigma^h \approx f_N^2 \lambda_{\phi_2^0}^2 / 4\pi \times \left(\frac{m_N^2}{m_{DM} m_h^2}\right)^2, \tag{39}$$

and

$$\sigma_{1\text{-}loop} = \frac{9 f_N^2 \pi \alpha_2^4 m_N^4}{64 M_W^2}\left(\frac{1}{M_W^2} + \frac{1}{m_h^2}\right)^2. \tag{40}$$

The later contribution is very interesting because it is independent of DM mass which sets a lower bound around 10^{-10} pb [9]. Although it is beyond the current experimental sensitivity but it is testable in next-generation experiments.

The masses of some new particles in our model are reachable at LHC, however, the production rates depend one the details of the parameters. The productions are dominated by the processes $q+\bar{q} \to Z^* \to X + \bar{X}$, where X represents S^-, ϕ_2, and Ψ'_i, and $q+q' \to W^* \to \phi_2^-(\Psi_i'^-) + \phi_2^0(\Psi_i'^0)$. Note the new particles must be produced in pairs according to Z_2 symmetry. The novel signatures will be the missing energy while producing the DM (ϕ_2^0), and the decays of ϕ_2^- and $\Psi_i'^-$ are mainly into $\phi_2^0\pi^-$ and $\Psi_i'^0\pi^-$ respectively. The charged particles in our model will leave charged tracks in detectors and provide clean signatures due to their long lifetimes. The pair of S^- and ϕ_2^+ can only be produced through the SM Higgs h and the corresponding coupling is proportional to the scale μ.

3. Summary and discussions

In summary, we propose an interesting model trying to address neutrino mass, muon anomalous magnetic moment, dark matter, lithium problem and TeV-scale leptogenesis within a single framework. The tiny neutrino mass and muon anomalous magnetic moment are generated through loops and also controlled by the mixing between charged scalars which is associated with the scale parameter μ. The inert doublet scalar can be identified as the dark matter candidate and its relic abundance was studied. The model can fulfill the CBBN scheme for the lithium problem because it contains a long-lived negative charged particle S^- where the long lifetime is due to the phase space suppression because of the nearly degenerate masses in charged scalars and their mixing parameter μ. However, the model cannot solve the problem of baryon asymmetry in the Universe through the TeV-scale leptogenesis. The nearly degenerate spectrum of the particle content will give interesting collider phenomena and can be tested in the near future.

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