

Dark Matter and Gauge Coupling Unification in Non-SUSY SO(10) Grand Unified Models

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The stability of dark matter is naturally explained if there is an additional U(1) symmetry which is spontaneously broken to a discrete symmetry at a high-energy scale. Such a framework is realized in the context of the SO(10) grand unification. In this work, we discuss dark matter models in the non-supersymmetric SO(10) grand unified models in which the stability of dark matter is assured by this mechanism. We find that the requirement of gauge coupling unification with a sufficiently high unification scale to evade the proton decay constraints plays an important role in selecting viable candidates. Some of the dark matter models can be tested in future dark matter direct searches and proton decay experiments.

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1. Introduction

A variety of cosmological observations has provided strong evidences for the existence of dark matter (DM). One of the distinct properties of dark matter is its stability; for a particle to be a good DM candidate, it should be stable or have a lifetime longer than the age of the Universe. To insure the stability, it is often assumed that there exists a discrete symmetry which prevents a DM particle from decaying into the Standard Model (SM) particles. For instance, the R -parity in the minimal supersymmetric (SUSY) SM allows the lightest SUSY particle to be a good DM candidate. It is quite often the case, however, that the origin of such a discrete symmetry is unclear and thus its introduction seems more or less ad hoc. Thus, it is of great interest if we can find some mechanism to generate a discrete symmetry that makes DM stable.

In fact, we can easily obtain a discrete symmetry if there is an additional U(1) gauge symmetry beyond the SM gauge symmetries which is spontaneously broken at a high-energy scale. Suppose that there is a U(1) gauge symmetry for which generic fields (including SM fields) φ_i and a Higgs field φ_H have charges Q_i and Q_H , respectively. Here, we normalize these charges so that they are integers. We further assume that the charge of the Higgs field φ_H satisfies $Q_H \equiv 0 \pmod{N}$ with N being a positive integer. A vacuum expectation value (VEV) of this Higgs field $\langle \varphi_H \rangle$ breaks the extra U(1) symmetry. An important observation here is that both the Lagrangian of the theory and the VEV $\langle \varphi_H \rangle$ are invariant under the following transformations:

$$\varphi_i \rightarrow \exp\left(\frac{i2\pi Q_i}{N}\right) \varphi_i, \quad \langle \varphi_H \rangle \rightarrow \exp\left(\frac{i2\pi Q_H}{N}\right) \langle \varphi_H \rangle = \langle \varphi_H \rangle. \quad (1.1)$$

This indicates that $\langle \varphi_H \rangle$ breaks the extra U(1) symmetry into a \mathbb{Z}_N symmetry [3, 4, 5, 6, 7].

We can consider such an extra U(1) symmetry within the context of the SO(10) grand unification [8, 9], as SO(10) is a rank-five gauge group. Indeed, the SO(10) grand unified theories (GUTs) have various attractive features. The SM quarks and leptons as well as three right-handed neutrinos are embedded into three generations of **16** spinor representations. Since SO(10) gauge theory is free from gauge anomalies, the anomaly cancellation in the SM can naturally be explained. In addition, SO(10) GUTs can realize gauge coupling unification even without SUSY with the aid of intermediate gauge symmetries (for a review of non-SUSY SO(10) GUTs with intermediate gauge symmetries, see Ref. [10]). In this case, masses of right-handed neutrinos are of the order of the intermediate gauge symmetry breaking scale M_{int} , which explains small neutrino masses via the seesaw mechanism [11, 12, 13, 14, 15, 16] if M_{int} is sufficiently high.

In the non-SUSY SO(10) GUTs, the extra U(1) symmetry is broken at the intermediate scale M_{int} . Thus, by appropriately choosing the Higgs field that breaks the intermediate gauge symmetry, we can obtain a remnant discrete symmetry at low energies according to the mechanism discussed above. In fact, it turns out that if a VEV of a **126** (**672**) of SO(10) breaks the intermediate gauge symmetry, then a \mathbb{Z}_2 (\mathbb{Z}_3) symmetry appears below the intermediate scale [17]. In particular, if we restrict ourselves to consider SO(10) multiplets whose dimensions are ≤ 210 , then the \mathbb{Z}_2 symmetry is the only possibility to be realized in such a framework. This \mathbb{Z}_2 symmetry is found to be equivalent to the so-called matter parity, $P_M = (-1)^{3(B-L)}$; this is not surprising as SO(10) contains the $B-L$ symmetry. Since the SM fermions have the matter parity odd and the SM Higgs field has the matter parity even, a boson (fermion) with the matter parity odd (even) cannot decay

into the SM particles in the presence of this \mathbb{Z}_2 symmetry. Thus, SO(10) GUTs can nicely explain the stability of DM with this remnant \mathbb{Z}_2 symmetry [18, 19, 20, 21].

In this work, we systematically study possibilities of DM in SO(10) GUT models which is stabilized with this mechanism. We find that two classes of DM candidates can be realized in this setup; one is the non-equilibrium thermal DM (NETDM) [22] and the other is the weakly-interacting massive particles (WIMPs). The former DM is a SM singlet fermion which is non-thermally produced from the scattering of SM particles in the thermal bath through the intermediate/GUT scale particle exchange. We discuss this case in the next section following the study in Ref. [1]. For the latter case, DM can be either a scalar or a fermion, and has a sizable interaction with the SM particles so that it can be thermalized in the early Universe. The WIMP DM in SO(10) GUTs is thoroughly discussed in Ref. [2], and we briefly review the result in Sec. 3. We focus on SO(10) GUT models in which gauge coupling unification is achieved with a sufficiently high GUT scale to evade constraints coming from proton decay experiments. We also check whether these models yield the correct DM density and account for small neutrino masses.

Throughout this article, we consider the following symmetry-breaking chain,

$$\text{SO}(10) \longrightarrow G_{\text{int}} \longrightarrow \text{SU}(3)_C \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y \otimes \mathbb{Z}_2, \quad (1.2)$$

where the SO(10) GUT group is broken at the GUT scale M_{GUT} into the intermediate gauge group G_{int} by a VEV of the GUT-scale Higgs multiplet R_1 . This intermediate gauge group is subsequently broken to the SM gauge group at the intermediate scale M_{int} by a VEV of the intermediate-scale Higgs multiplet R_2 . The GUT and intermediate scales are determined using the condition of gauge coupling unification. We denote the DM multiplet by R_{DM} . Among the components in R_{DM} , only the DM field has a mass much lighter than the intermediate scale so that it can explain the observed DM density, while the other components are supposed to have masses of $\mathcal{O}(M_{\text{int}})$. Such a mass spectrum is obtained by fine-tuning of the coefficients in the original Lagrangian terms, just like the ordinary doublet-triplet splitting in the Higgs sector. We only consider SO(10) multiplets whose dimensions are equal to or less than 210 in the following discussion.

2. Singlet Fermion DM: NETDM

First, we discuss the case of SM singlet fermion DM. This class of DM candidates cannot couple to the SM sector at renormalizable level. Therefore, if new physics appears at a very high scale (M_{int} in the present setup), the DM interactions with SM particles are so weak that this DM cannot be in thermal equilibrium in the early Universe. Nevertheless, such a DM particle can be produced via the NETDM mechanism [22] as we discuss below.

For a fermion to be stabilized by the \mathbb{Z}_2 symmetry in Eq. (1.2), it should have an even parity under the symmetry. It is found that a SM singlet fermion which has an even \mathbb{Z}_2 charge appears in a **45**, **54**, **126**, or **210** of SO(10). By requiring gauge coupling unification with a sufficiently high GUT scale, we have found two promising models which contain singlet fermion DM.¹ We

¹Here, we have assumed the DM multiplet to be charged under the intermediate gauge symmetry. In this case, the DM can be produced via the exchange of the intermediate-scale particles. We can also consider the case where the DM multiplet is also singlet under the intermediate gauge symmetry. This DM can still be produced via the GUT-scale interactions. Such a possibility is also discussed in Ref. [1].

| | Model I | Model II |
|------------------|---|---|
| G_{int} | $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$ | $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \otimes D$ |
| R_{DM} | $(\mathbf{1}, \mathbf{1}, \mathbf{3})_D$ in $\mathbf{45}_D$ | $(\mathbf{15}, \mathbf{1}, \mathbf{1})_W$ in $\mathbf{45}_W$ |
| R_1 | $\mathbf{210}_R$ | $\mathbf{54}_R$ |
| R_2 | $(\mathbf{10}, \mathbf{1}, \mathbf{3})_C \oplus (\mathbf{1}, \mathbf{1}, \mathbf{3})_R$ | $(\mathbf{10}, \mathbf{1}, \mathbf{3})_C \oplus (\mathbf{10}, \mathbf{3}, \mathbf{1})_C \oplus (\mathbf{15}, \mathbf{1}, \mathbf{1})_R$ |
| M_{int} | 1.2×10^8 GeV | 4.6×10^{13} GeV |
| M_{GUT} | 4.4×10^{15} GeV | 7.4×10^{15} GeV |
| g_{GUT} | 0.53 | 0.57 |

Table 1: Singlet fermion DM models [1].

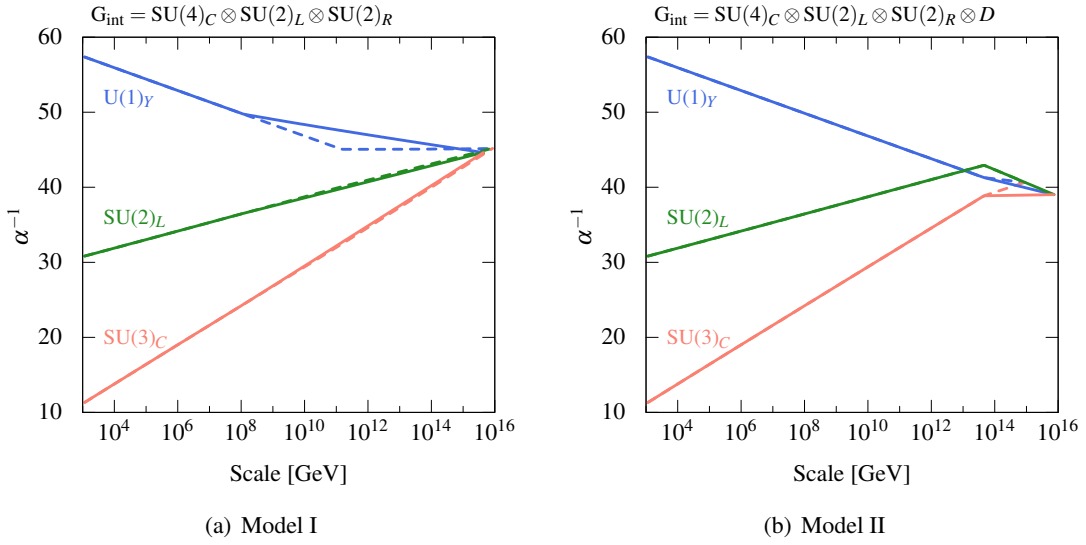


Figure 1: Running of gauge couplings [1]. Solid (dashed) lines show the case with (without) DM and additional Higgs bosons. Blue, green, and red lines represent the running of the $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ gauge couplings, respectively.

summarize the contents of these models in Table 1. One of the models has an intermediate gauge symmetry of $G_{\text{int}} = SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$, while the other has $G_{\text{int}} = SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \otimes D$ with D representing the left-right parity—an additional discrete symmetry with respect to the interchange of left- and right-handed fields. We refer to the former (latter) as Model I (II) in what follows. In Model I, the singlet fermion DM stays inside the $(\mathbf{1}, \mathbf{1}, \mathbf{3})_D$ component of a $\mathbf{45}_D$ of $SO(10)$, while in Model II it is in the $(\mathbf{15}, \mathbf{1}, \mathbf{1})_W$ of a $\mathbf{45}_W$. Here, the subscripts R , C , W , and D indicate a real scalar boson, a complex scalar boson, a Weyl fermion, and a Dirac fermion, respectively. The $(\mathbf{10}, \mathbf{1}, \mathbf{3})_C$ component appearing in R_2 originates from a $\mathbf{126}_C$, whose VEV yields the remnant \mathbb{Z}_2 symmetry. The other Higgs fields in R_2 are introduced to give masses of $\mathcal{O}(M_{\text{int}})$ to all of the components in R_{DM} except the DM field. The GUT and intermediate scales as well as the unified gauge coupling g_{GUT} in Table 1 are evaluated by using the two-loop renormalization group equations (RGEs). We also show the running of the gauge couplings in these models in Fig. 1.

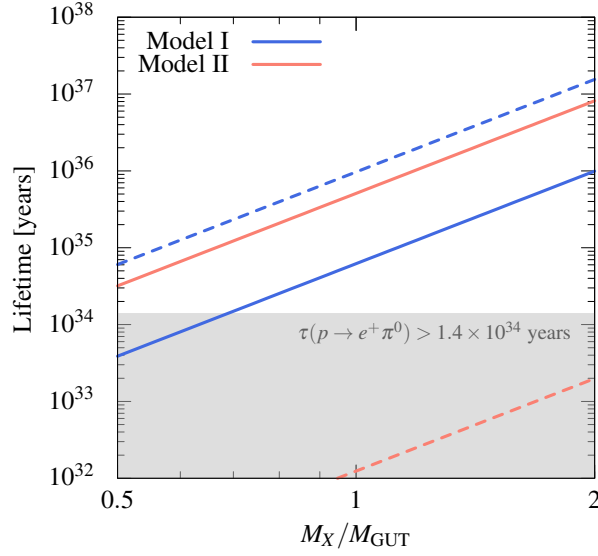


Figure 2: Proton lifetimes as functions of M_X/M_{GUT} [1]. Blue and red solid lines correspond to Model I and II, respectively. Blue and red dashed lines represent the cases for $G_{\text{int}} = \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R$ and $G_{\text{int}} = \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R \otimes D$, respectively, where the DM and extra Higgs multiplets are not included. Shaded region shows the current experimental bound, $\tau(p \rightarrow e^+ \pi^0) > 1.4 \times 10^{34}$ years [23].

Here, the solid and dashed lines show the cases with and without DM and additional intermediate-scale Higgs multiplets, respectively. The $U(1)_Y$ gauge coupling constant above the intermediate scale is defined by $\frac{1}{\alpha_Y} \equiv \frac{3}{5} \frac{1}{\alpha_{2R}} + \frac{2}{5} \frac{1}{\alpha_4}$ where α_{2R} (α_4) is the $\text{SU}(2)_R$ ($\text{SU}(4)_C$) gauge coupling, while the $\text{SU}(3)_C$ gauge coupling above M_{int} is given by $\alpha_3 \equiv \alpha_4$. As can be seen from the plots, the presence of the DM and extra intermediate-scale Higgs multiplets significantly affects the running of the gauge coupling constants.

As we have obtained the GUT scales in the models, we can now evaluate proton decay lifetimes for each model. In the non-SUSY GUTs, proton decay is induced by the exchange of the GUT-scale gauge bosons. The dominant decay mode in this case is the $p \rightarrow e^+ \pi^0$ process. A calculation of proton decay rates in SO(10) GUTs is presented in Appendix B in Ref. [2], and we follow the prescription given there. We show the resultant proton decay lifetimes in the models in Fig. 2. Here, the blue solid and red solid lines represent proton lifetimes in Model I and II, respectively, while the dashed lines correspond to the cases in which the DM and extra Higgs multiplets are not included. Proton lifetimes depend on the GUT-scale gauge boson mass M_X . Although M_X is expected to be of the order of the GUT scale, its precise value cannot be determined from low energies, and this ignorance therefore causes uncertainty in the proton decay calculation. Considering this, we estimate the uncertainty by varying M_X from $M_{\text{GUT}}/2$ to $2M_{\text{GUT}}$ in this plot. The gray shaded region in Fig. 2 shows the current experimental bound, $\tau(p \rightarrow e^+ \pi^0) > 1.4 \times 10^{34}$ years [23]. From this figure, we find that proton lifetimes for $M_X \simeq M_{\text{GUT}}$ lie above the current constraint in both of the models. Notice that the presence of the DM and extra Higgs multiplets gives a significant impact on the prediction of proton lifetimes; indeed, in the absence of these particles, the $G_{\text{int}} = \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R \otimes D$ case predicts too rapid proton decay rate to evade the

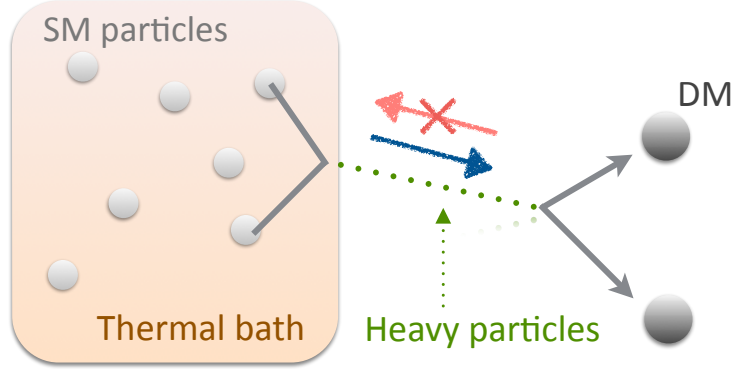


Figure 3: The NETDM mechanism [22] for DM production.

current experimental limit, but the addition of these particles makes Model II viable. Anyway, in both of these models, proton decay lifetimes are predicted to be rather short. Hence, these models may be probed in future proton decay experiments.

Next, we consider neutrino masses in these models. In both of the models, neutrino masses are given by the ordinary seesaw mechanism [11, 12, 13, 14, 15, 16]. An important caveat here is that in the case of SO(10) GUTs Dirac Yukawa couplings for neutrinos are related to other Yukawa couplings. In particular, since the SU(4)_C symmetry is manifest above M_{int} in our models and a VEV of the (1, 2, 2) component, which is identified as the SM Higgs field in the minimal setup, does not break the SU(4)_C symmetry, the Dirac masses of neutrinos are equal to up-quark masses m_{u_i} up to logarithmic corrections in the low-energy region. As a consequence, neutrino masses m_{ν_i} are given by

$$m_{\nu_i} \simeq \frac{m_{u_i}^2}{M_{\text{int}}}, \quad (2.1)$$

where we have used the fact that Majorana masses for right-handed neutrinos are $\mathcal{O}(M_{\text{int}})$. From the results given in Table 1, we then find that the Model II predicts neutrino masses compatible with the present data, while those in Model I are too large. This is because of a low intermediate scale in Model I, as can be seen from Fig. 1(a). In this sense, Model II is more favorable than Model I. A simple way to make Model I viable is to exploit the (15, 2, 2) component of the 126 Higgs multiplet. This component contains an SU(2)_L doublet Higgs field, which can have a VEV of the order of the electroweak scale. Since this VEV breaks the SU(4)_C symmetry, one can choose its VEV and Yukawa couplings such that its contribution to Dirac mass terms of neutrinos cancels the above contribution. In this case, we can evade the relation (2.1), and desirable neutrino masses can be obtained even with a low intermediate scale. We also find that the presence of a (15, 2, 2) field scarcely affects gauge coupling unification, as it changes the beta functions of all of the gauge coupling constants by similar amounts [24]. Therefore, the introduction of a (15, 2, 2) resolves the neutrino mass problem in Model I without largely modifying the GUT and intermediate scales obtained above.

Now we consider the DM production mechanism in these models. As mentioned above, DM particles in these models do not come into thermal equilibrium in the early Universe as long as

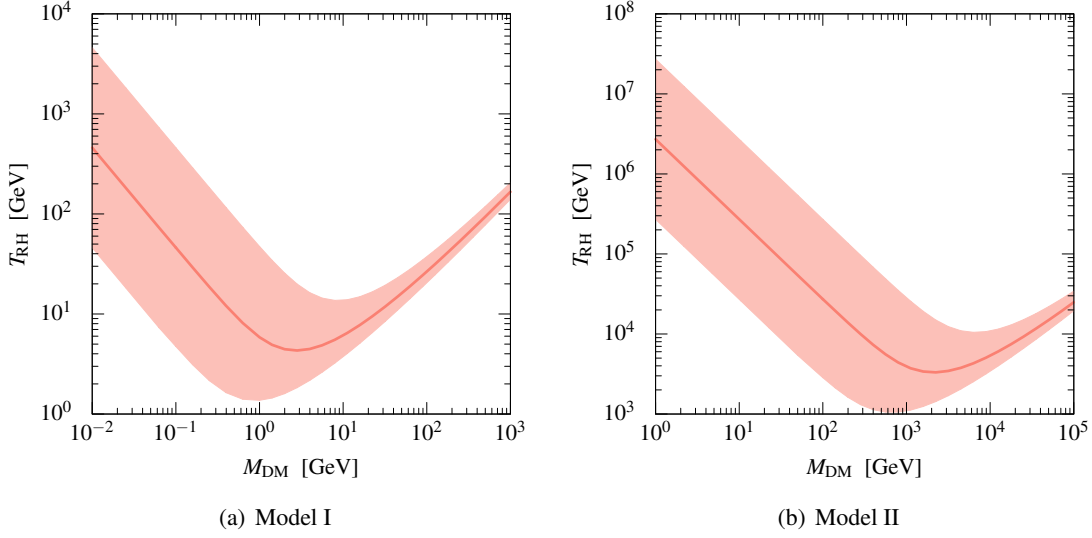


Figure 4: Reheating temperature as a function of M_{DM} [1]. Pink band shows the theoretical uncertainty.

the reheating temperature T_{RH} is lower than the intermediate scale. In this case, DM is produced non-thermally from the scattering of the SM particles in the thermal bath through the exchange of intermediate/GUT scale particles. The pair annihilations of DM particles during the DM production are negligible. This situation is illustrated in Fig. 3. The current DM abundance in this case is evaluated by using the following Boltzmann equation:

$$\frac{dY_{DM}}{dx} = \sqrt{\frac{\pi g_*}{45}} M_{DM} M_{Pl} \frac{\langle \sigma v \rangle}{x^2} Y_{eq}^2, \quad (2.2)$$

where $Y_{DM} \equiv n_{DM}/s$, $Y_{eq} \equiv n_{eq}/s$, n_{DM} is the number density of DM, n_{eq} is the equilibrium number density of each individual initial state SM particle, s is the entropy of the Universe, $x \equiv M_{DM}/T$, T is the temperature of the Universe, M_{DM} is the DM mass, $M_{Pl} \equiv 1/\sqrt{G_N} = 1.22 \times 10^{19}$ GeV, g_* is the effective degrees of freedom in the thermal bath, and $\langle \sigma v \rangle$ denotes the thermally averaged total annihilation cross section of the initial SM particles into the DM pair. Notice that there is no self-annihilation contribution in the right-hand side in Eq. (2.2), as mentioned above. By solving this equation, we can obtain DM relic abundance as a function of M_{DM} and T_{RH} .

In Fig. 4, we show the regions favored by the DM relic abundance in the M_{DM} - T_{RH} plane for each model. Here, the pink bands indicate the uncertainty of our computation. We see that Model I predicts low value of T_{RH} except for the fine-tuning region $T_{RH} \simeq M_{DM}$. For such a low reheating temperature, baryogenesis is usually quite challenging. On the other hand, T_{RH} can be sufficiently high in the case of Model II. Thus, Model II is again favored compared to Model I.

3. WIMP DM Candidates

Next, we briefly discuss WIMP DM in the SO(10) GUT models. For systematic classification of such possibilities and detailed discussions on the models, see Ref. [2]. In the case of WIMP DM, we have both scalar and fermion candidates. For a scalar particle to be stable, it should

have odd matter parity, which can originate from either a **16** or **144** of SO(10). By requiring a sufficiently high unification scale to ensure a proton decay lifetime compatible with the current experimental limits, we find that only the SM singlet DM or the SU(2)_L doublet with hypercharge $Y = \pm 1/2$ scalar DM can be realized in the low-energy regions, with possible intermediate scales being SU(4)_C ⊗ SU(2)_L ⊗ SU(2)_R, SU(3)_C ⊗ SU(2)_L ⊗ SU(2)_R ⊗ U(1)_{B-L}, or SU(3)_C ⊗ SU(2)_L ⊗ SU(2)_R ⊗ U(1)_{B-L} ⊗ D. The former case, in which a singlet scalar is added to the SM as a DM candidate, is one of the simplest extensions of the SM and has widely been discussed so far [25, 26, 27]. The latter DM candidate is often called the inert Higgs doublet DM [28, 29, 30, 31]. As for fermionic DM candidates, we obtain an SU(2)_L triplet $Y = 0$ DM candidate from a **45** of SO(10), though it requires additional Higgs multiplets around the intermediate scale to realize good gauge coupling unification. We can also find SU(2)_L doublet DM candidates. Such a DM candidate in general requires extra Majorana fermions beyond the DM multiplet; otherwise the DM candidate becomes a Dirac fermion and such a possibility has already been excluded by direct detection experiments since Dirac fermion DM with non-zero hypercharge has a large DM-nucleon scattering cross section. To evade the constraint, the SU(2)_L doublet DM has to mix with the extra Majorana fermions to be split into two pseudo-Dirac fermions. Moreover, to also suppress the inelastic scattering of the DM with nucleons, the mass difference between these pseudo-Dirac fermions should be $\gtrsim 100$ keV [32]. This condition gives an upper bound on the masses of the extra Majorana fermions [33], and if we assume these masses to be $\mathcal{O}(M_{\text{int}})$, this bound leads to an upper bound on M_{int} . Taking into account this constraint, as well as that from proton decay bounds, we found several models for the SU(2)_L doublet DM, which turn out to have either $G_{\text{int}} = \text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R$ or $\text{SU}(4)_C \otimes \text{SU}(2)_L \otimes \text{U}(1)_R$. These non-SUSY SO(10) WIMP DM models can be tested in future DM direct searches and proton decay experiments.

4. Conclusion and Discussions

In this work, we have discussed DM candidates in non-SUSY SO(10) GUT models with an intermediate gauge symmetry. In these models, the stability of DM is achieved thanks to a remnant \mathbb{Z}_2 symmetry which is a subgroup of SO(10). The DM can be either NETDM or WIMP DM. For both cases, the requirement of gauge coupling unification with a sufficiently high GUT scale to evade the proton decay limit plays a significant role in selecting viable candidates. In the case of NETDM, we found two promising models which satisfy the above condition. The DM particles in these models are non-thermally produced from the scattering of the SM particles in the thermal bath via the exchange of intermediate-scale particles; we have computed the favored reheating temperature which yields the correct DM density. As for the WIMP DM case, we have found models that include a SM singlet, an inert Higgs doublet, an SU(2)_L triplet, or an SU(2)_L doublet DM candidate. In any cases, future DM direct searches and proton decay experiments can probe these DM models.

Finally, we would like to comment on some previous studies. In Refs. [18, 19], a SM singlet scalar and SU(2)_L doublet scalar DM originating from a **16** of SO(10) are considered, where SO(10) is assumed to be broken to SU(5) ⊗ U(1)_X and this U(1)_X is broken to the \mathbb{Z}_2 symmetry. Gauge coupling unification and the proton decay constraints are not discussed in detail. In Ref. [20], on the other hand, both scalar and fermion DM candidates are discussed. Intermediate gauge symmetries

are not discussed there, and for this reason, an $SU(2)_L$ triplet with $Y = 0$ is found to be the only promising candidate for DM which may make the unification scale high enough, though gauge coupling unification is challenging if one focuses on minimal field contents.

Acknowledgments

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