


$SO(10) \rightarrow SU(5) \times U(1)_\chi$ as the origin of dark matter

Ernest Ma

*Physics and Astronomy Department, University of California, Riverside, California 92521, USA
and Jockey Club Institute for Advanced Study, Hong Kong University of Science and Technology,
Hong Kong, China* (Received 30 October 2018; published 27 November 2018)

In the decomposition of $SO(10)$ grand unification to $SU(5) \times U(1)_\chi$, two desirable features are obtained with the addition of one colored fermion octet Ω , one electroweak fermion triplet Σ and one complex scalar triplet S to the particle content of the standard model with two Higgs doublets. They are (1) gauge coupling unification of $SU(3)_C \times SU(2)_L \times U(1)_Y$ to $SU(5)$, and (2) the automatic (predestined) emergence of dark matter, i.e., Ω , Σ and S , with dark parity given by $(-1)^{Q_\chi+2j}$. It suggests that $U(1)_\chi$ may well be the underlying symmetry of the dark sector.

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I. INTRODUCTION

The origin of dark matter and the symmetry which maintains it are important issues in particle and astroparticle physics. A prevalent supposition is supersymmetry which admits superparticles as belonging to the dark sector if R parity is imposed. Great hope was attached to the Large Hadron Collider (LHC) in discovering supersymmetry at the present 13 TeV total center-of-mass energy, but no sign of such has yet been reported. Is there another underlying framework for dark matter? More importantly, does this underlying framework provide as well the dark symmetry required [1,2], instead of having it imposed as in supersymmetry? The answer, as suggested in this paper, is $U(1)_\chi$ which is the possible residual symmetry in the breaking of $SO(10)$ to $SU(5)$.

In most studies of $SO(10)$ grand unification, the breaking to a left-right extension of the standard model is considered. In that case, since $U(1)_{B-L}$ is an Abelian gauge factor in the decomposition $SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ with the electric charge $Q = I_{3L} + I_{3R} + (B-L)/2$, the parity $(-1)^{3(B-L)+2j}$ may be used to distinguish matter from dark matter and coincides with the R parity of supersymmetry. Many studies [3–12] have been made using this obvious connection. On the other hand, the (trivial) breaking of $SO(10)$ to $SU(5)$ is usually considered to be uninteresting, because it reduces to studying $SU(5)$ grand unification by itself. The possible residual $U(1)_\chi$ symmetry is treated as an

unimportant peripheral issue, allowing LHC data to put a limit on the Z_χ boson mass of about 4.1 TeV [13,14].

Whereas examples of automatic (predestined) dark matter are possible in the standard model (SM) itself [1] or some of its simple gauge extensions [2], their origin is unexplained. In the context of $U(1)_\chi$, because all SM fermions have odd charge Q_χ and all SM bosons have even Q_χ , the dark sector in this framework consists simply of all fermions with even Q_χ and scalars with odd Q_χ . The stability symmetry of dark matter is thus revealed to be $(-1)^{Q_\chi+2j}$. Note the important fact that Q_χ is not part of the electric charge, whereas $B-L$ is. This means that Z_χ is independent of the photon as well as the Z boson, whereas the $B-L$ gauge boson would not be. Note that each complete fermion multiplet of $SU(5)$, i.e., 5^* or 10, has its own unique Q_χ , i.e., 3 or -1 , whereas the complete fermion multiplet $\underline{16}$ of $SO(10)$ has different $B-L$ for its various components, separated by its $SU(3)_C \times SU(2)_L \times SU(2)_R$ content. Consequently, Q_χ is more desirable than $B-L$ as a marker of dark matter. There is also an important difference in their corresponding phenomenology. The $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$ model assumes that there is no intermediate symmetry breaking scale for $SU(5)$, whereas the $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model assumes an intermediate scale where $SU(2)_R \times U(1)_{B-L}$ breaks to $U(1)_Y$. Even though $U(1)_\chi \times U(1)_Y$ is equivalent to $U(1)_{B-L} \times I_{3R}$, the charged gauge bosons W_R^\pm appear in the latter scenario but not in the former.

To find a marker for $SO(10)$ multiplets, consider the decomposition $E_6 \rightarrow SO(10) \times U(1)_\psi$, with

$$\underline{27} = (16, -1) + (10, 2) + (1, -4). \quad (1)$$

In that case, Q_ψ takes the role of Q_χ , and Z_ψ is independent of the three neutral gauge bosons of $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

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Furthermore, under $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$, if the fermions $\Omega \sim (8, 1, 0, 0)$ and $\Sigma \sim (1, 3, 0, 0)$ are added together with the scalar $S \sim (1, 3, 0, -5)$ at the TeV scale, then $SU(5)$ gauge unification is achieved with $M_U \sim 10^{16}$ GeV. This is a new realization where the particles added to those of the SM are all in the dark sector. It suggests that matter and dark matter are related to each other [15]. It is also qualitatively different from previous studies requiring $SO(10)$ gauge unification. In particular, the scalar triplet S from the 144 of $SO(10)$ is unique to this proposal.

II. DECOMPOSITION OF $SO(10)$ TO $SU(5) \times U(1)_\chi$

Consider first the 16 representation of $SO(10)$ which contains all the SM fermions. Under its $SU(5) \times U(1)_\chi$ decomposition, it is well-known that

$$\underline{16} = (5^*, 3) + (10, -1) + (1, -5), \quad (2)$$

whereas the 10 representation contains the necessary Higgs doublets, i.e.,

$$\underline{10} = (5^*, -2) + (5, 2). \quad (3)$$

Under $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$,

$$\begin{aligned} (5^*, 3) &= d^c[3^*, 1, 1/3, 3] + (\nu, e)[1, 2, -1/2, 3], \\ (1, -5) &= \nu^c[1, 1, 0, -5], \end{aligned} \quad (4)$$

$$\begin{aligned} (10, -1) &= u^c[3^*, 1, -2/3, -1] + (u, d)[3, 2, 1/6, -1] \\ &\quad + e^c[1, 1, 1, -1], \end{aligned} \quad (5)$$

$$\begin{aligned} \Phi_1 &= (\phi_1^0, \phi_1^-)[1, 2, -1/2, -2], \\ \Phi_2 &= (\phi_2^+, \phi_2^0)[1, 2, 1/2, 2]. \end{aligned} \quad (6)$$

Hence the allowed Yukawa couplings are

$$\begin{aligned} d^c(u\phi_1^- - d\phi_1^0), &\quad u^c(u\phi_2^0 - d\phi_2^+), \\ e^c(\nu\phi_1^- - e\phi_1^0), &\quad \nu^c(\nu\phi_2^0 - e\phi_2^+), \end{aligned} \quad (7)$$

as desired. Note that $U(1)_\chi$ is broken by 2 units as $\phi_{1,2}^0$ acquire nonzero vacuum expectation values. Now the 126 representation of $SO(10)$ contains a singlet $\zeta \sim (1, -10)$ under $SU(5) \times U(1)_\chi$. Such a scalar may be used to break $U(1)_\chi$ at the TeV scale and would allow ν^c (the right-handed neutrino) to obtain a large Majorana mass, thereby triggering the canonical seesaw mechanism for small Majorana neutrino masses. This is usually described as lepton number L breaking to lepton parity $(-1)^L$ [16], but here it is clear that it has to do with the breaking of gauge $U(1)_\chi$ to $(-1)^{Q_\chi}$.

At this stage, all SM fermions are odd and all SM bosons are even under $(-1)^{Q_\chi}$. Hence they are all even under

$$R_\chi = (-1)^{Q_\chi + 2j}. \quad (8)$$

This suggests strongly that a dark sector exists where Q_χ is even for fermions and odd for scalars so they all have odd R_χ . The next step is to identify possible candidates which will also enforce gauge $SU(5)$ unification, thus justifying the role of $U(1)_\chi$ as the residual symmetry from the breaking of $SO(10)$ to $SU(5)$.

III. GAUGE $SU(5)$ UNIFICATION FROM THE ADDITION OF DARK MATTER

To break $SO(10)$ to $SU(5) \times U(1)_\chi$, the scalar 45 is used. Since

$$\underline{45} = (24, 0) + (10, 4) + (10^*, -4) + (1, 0) \quad (9)$$

under $SU(5) \times U(1)_\chi$, a nonzero vacuum expectation value (VEV) of the $(1, 0)$ component will work. Under $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$,

$$\begin{aligned} (24, 0) &= (8, 1, 0, 0) + (1, 3, 0, 0) + (3, 2, 1/6, 0) \\ &\quad + (3^*, 2, -1/6, 0) + (1, 1, 0, 0). \end{aligned} \quad (10)$$

Hence a nonzero VEV of the $(1, 1, 0, 0)$ component will break $SU(5) \times U(1)_\chi$ to the SM gauge symmetry without breaking $U(1)_\chi$. The electroweak symmetry breaking occurs through the nonzero VEVs of $\phi_{1,2}^0$ and $U(1)_\chi$ is broken at the TeV scale through the scalar $\zeta \sim (1, -10)$ singlet, as discussed in the previous section.

The particle content so far consists of all the SM fermions and gauge bosons together with two Higgs doublets and one singlet. There is also the Z_χ gauge boson at the TeV scale. Experimentally, the three gauge couplings corresponding to $SU(3)_C \times SU(2)_L \times U(1)_Y$ are measured, but it is well-known that they do not extrapolate to a single value at a possible unification scale, based on this particle content. On the other hand, this may be achieved simply with the addition of two fermion and one scalar multiplets, all belonging to the dark sector at the TeV scale.

Consider the one-loop renormalization-group equations governing the evolution of gauge couplings with mass scale:

$$\frac{1}{\alpha_i(M_1)} - \frac{1}{\alpha_i(M_2)} = \frac{b_i}{2\pi} \ln \frac{M_2}{M_1}, \quad (11)$$

where $\alpha_i = g_i^2/4\pi$ and the numbers b_i are determined by the particle content of the model between M_1 and M_2 . In the SM with one Higgs scalar doublet, these are given by

$$SU(3)_C: b_C = -11 + (4/3)N_F = -7, \quad (12)$$

$$SU(2)_L: b_L = -22/3 + (4/3)N_F + 1/6 = -19/6, \quad (13)$$

$$U(1)_Y: b_Y = (4/3)N_F + 1/10 = 41/10, \quad (14)$$

where $N_F = 3$ is the number of quark and lepton families and b_Y has been normalized by the well-known factor of $3/5$. A second Higgs doublet at M_ϕ would contribute $\Delta b_L = 1/6$ and $\Delta b_Y = 1/10$.

Suppose a colored fermion octet $\Omega \sim (8, 1, 0, 0)$ is added with M_Ω as well as an electroweak fermion triplet $\Sigma \sim (1, 3, 0, 0)$ with M_Σ , both coming from the $(24, 0)$ of Eq. (10). These are then augmented by an electroweak scalar triplet $S \sim (1, 3, 0, -5)$ with M_S , coming from the $SO(10)$ scalar representation 144, i.e.,

$$\begin{aligned} \underline{144} = & (5^*, 3) + (5, 7) + (10, -1) + (15, -1) \\ & + (24, -5) + (40, -1) + (45^*, 3), \end{aligned} \quad (15)$$

which contains $(24, -5)$ and thus $(1, 3, 0, -5)$. Note that

$$\underline{16}^* \times \underline{10} = \underline{16} + \underline{144}. \quad (16)$$

As a result, Ω contributes $\Delta b_C = (2/3)3 = 2$, Σ contributes $\Delta b_L = (2/3)2 = 4/3$, and S contributes $\Delta b_L = (1/3)2 = 2/3$. Note that Ω , Σ , and S all have odd R_χ . Assuming unification at M_U and normalizing α_Y by $5/3$, the evolution equations are then given by

$$\frac{1}{\alpha_U} = \frac{1}{\alpha_C} + \frac{5}{2\pi} \ln \frac{M_U}{M_Z} + \frac{2}{2\pi} \ln \frac{M_\Omega}{M_Z}, \quad (17)$$

$$\begin{aligned} \frac{1}{\alpha_U} = & \frac{1}{\alpha_L} + \frac{1}{2\pi} \ln \frac{M_U}{M_Z} + \frac{1}{2\pi} \left(\frac{1}{6}\right) \ln \frac{M_\phi}{M_Z} + \frac{1}{2\pi} \left(\frac{4}{3}\right) \ln \frac{M_\Sigma}{M_Z} \\ & + \frac{1}{2\pi} \left(\frac{2}{3}\right) \ln \frac{M_S}{M_Z}, \end{aligned} \quad (18)$$

$$\frac{1}{\alpha_U} = \frac{3}{5\alpha_Y} - \frac{1}{2\pi} \left(\frac{21}{5}\right) \ln \frac{M_U}{M_Z} + \frac{1}{2\pi} \left(\frac{1}{10}\right) \ln \frac{M_\phi}{M_Z}, \quad (19)$$

where $\alpha_C, \alpha_L, \alpha_Y$ are evaluated at M_Z . Their central values are [17]

$$\begin{aligned} \alpha_C = & 0.118, \quad \alpha_L = (\sqrt{2}/\pi)G_F M_W^2 = 0.0340, \\ \alpha_Y = & \alpha_L \tan^2 \theta_W = 0.0102. \end{aligned} \quad (20)$$

The idea that octets and triplets are important in $SU(5)$ gauge unification is not new [18–21]. However, the role of $U(1)_\chi$ was not recognized. Otherwise, the choice here follows closely that of Ref. [21]. Note that the chosen particle content is free of gauge anomalies even with the inclusion of $U(1)_\chi$. Eliminating α_U and using Eq. (20), the two conditions on $M_U, M_\Omega, M_\Sigma, M_S$ and M_ϕ are

$$\begin{aligned} 35.538 = & \ln \frac{M_U}{M_Z} + 0.2564 \ln \frac{M_\Sigma}{M_Z} \\ & + 0.1282 \ln \frac{M_S}{M_Z} + 0.0128 \ln \frac{M_\phi}{M_Z}, \end{aligned} \quad (21)$$

$$\begin{aligned} 32.888 = & \ln \frac{M_U}{M_Z} + 0.5 \ln \frac{M_\Omega}{M_Z} - 0.3333 \ln \frac{M_\Sigma}{M_Z} \\ & - 0.1667 \ln \frac{M_S}{M_Z} - 0.0417 \ln \frac{M_\phi}{M_Z}. \end{aligned} \quad (22)$$

Subtracting the two equations to eliminate M_U , the condition

$$\begin{aligned} 2.650 = & 0.5897 \ln \frac{M_\Sigma}{M_Z} + 0.2949 \ln \frac{M_S}{M_Z} \\ & + 0.0545 \ln \frac{M_\phi}{M_Z} - 0.5 \ln \frac{M_\Omega}{M_Z} \end{aligned} \quad (23)$$

is obtained. Assuming the neutral component Σ^0 to be dark matter, it has been shown some years ago [22] that $M_\Sigma \simeq 2.3$ TeV. Using that value and assuming the second Higgs doublet to have $M_\phi \simeq 500$ GeV, the constraint

$$0.654 = 0.2949 \ln \frac{M_S}{M_Z} - 0.5 \ln \frac{M_\Omega}{M_Z} \quad (24)$$

may be satisfied e.g., with $M_S = 2.5$ TeV and $M_\Omega = 174$ GeV, in which case $M_U = 6.93 \times 10^{16}$ GeV and $\alpha_U = 0.0278$.

IV. PHENOMENOLOGY OF THE DARK SECTOR

The dark sector consists of the scalar $S \sim (1, 3, 0, -5)$ and the fermions $\Sigma \sim (1, 3, 0, 0)$, $\Omega \sim (8, 1, 0, 0)$. They are the only particles beyond those of the SM (with two Higgs doublets) in addition to Z_χ and the scalar singlet $\zeta \sim (1, 1, 0, -10)$ which breaks $U(1)_\chi$. Consider first the colored fermion octet Ω . It is just like the gluino of supersymmetry, except that it is stable here because there are no scalar quarks. However, because it has strong interactions, bound states do exist [23–25] from the exchange of gluons. These gluinonia would then decay into quark pairs. At the LHC, they may be searched for, as shown in Ref. [25]. Since M_Ω is predicted here to be relatively light, this signature is a possible verification of its existence.

If $M_S > M_\Sigma$, then S decays to $\nu\Sigma$ through the $U(1)_\chi$ allowed $f_S S^* \nu^c \Sigma$ Yukawa coupling and the neutrino $\nu - \nu^c$ mixing $\sim \sqrt{m_\nu/M_R}$, with a decay rate

$$\Gamma = \frac{f_S^2 m_\nu M_S}{16\pi M_R} \left(1 - \frac{M_\Sigma^2}{M_S^2}\right)^2. \quad (25)$$

Assuming $m_\nu = 0.1$ eV, $M_R = 4$ TeV, $f_S = 0.01$, $M_S = 2.5$ TeV, $M_\Sigma = 2.3$ TeV, then this decay lifetime is 2.2×10^{-7} s which is certainly acceptable cosmologically.

In this scenario, Σ^0 is stable. Its relevance as dark matter has been studied in detail [22]. In particular, the radiative splitting of Σ^\pm with Σ^0 is known [26] to be positive from gauge boson interactions, but is limited [1] to 167 MeV. This means that whereas Σ^0 is the dark matter today, its relic abundance is determined in the early Universe with the coexistence of Σ^\pm , i.e., all annihilation channels involving Σ^0, Σ^\pm have to be considered. This was done in Ref. [22] and

$$2.28 < M_\Sigma < 2.42 \text{ TeV} \quad (26)$$

was obtained. Similar results are obtained in supersymmetry with a pure wino as dark matter [27]. The difference is that the wino has many other interactions which are absent in the case of Σ . As for direct detection, Σ^0 does not couple to the Z_χ or Z or any scalar at tree level, but may interact with quarks in one and two loops. However, these effects are known to be small [28], with the spin-independent cross section below 2×10^{-47} cm².

If $M_S < M_\Sigma$, then S^0 is dark matter. Since it is a scalar, it has possible quartic interactions with the two Higgs doublets and one singlet. Any such interaction must be suppressed to avoid the constraint from direct-search experiments because all R_χ even scalars couple to quarks. This means that the annihilation cross section of S^0 to scalars would be too small, so its relic abundance should again be determined by gauge interactions, as in the case of Σ .

V. PHENOMENOLOGY OF THE $U(1)_\chi$ SECTOR

The contribution of the SM particles to b_χ is

$$\begin{aligned} b_\chi &= \frac{1}{40} \left(\frac{2}{3} \right) [5(3)^2 + 10(-1)^2] N_F + \frac{1}{40} \left(\frac{1}{3} \right) [2(2)^2] \\ &= \frac{169}{60}, \end{aligned} \quad (27)$$

where the factor $1/40$ has been inserted to normalize Q_χ . The addition of a second Higgs doublet at M_ϕ contributes $\Delta b_\chi = 1/15$, and those of ν^c and the scalar singlet $\zeta \sim (1, 1, 0, -10)$ contribute $\Delta b_\chi = 25/12$, whereas S contributes $\Delta b_\chi = 5/8$. Hence

$$\begin{aligned} \frac{1}{\alpha_U} &= \frac{1}{\alpha_\chi} - \frac{1}{2\pi} \left(\frac{671}{120} \right) \ln \frac{M_U}{M_Z} + \frac{1}{2\pi} \left(\frac{1}{15} \right) \ln \frac{M_\phi}{M_Z} \\ &\quad + \frac{1}{2\pi} \left(\frac{5}{8} \right) \ln \frac{M_S}{M_Z} + \frac{1}{2\pi} \left(\frac{25}{12} \right) \ln \frac{M_R}{M_Z}. \end{aligned} \quad (28)$$

Using the previously determined values, $\alpha_\chi = 0.0154$ at M_Z is obtained. The one-loop evolutions of $1/\alpha_\chi, 3/5\alpha_Y,$

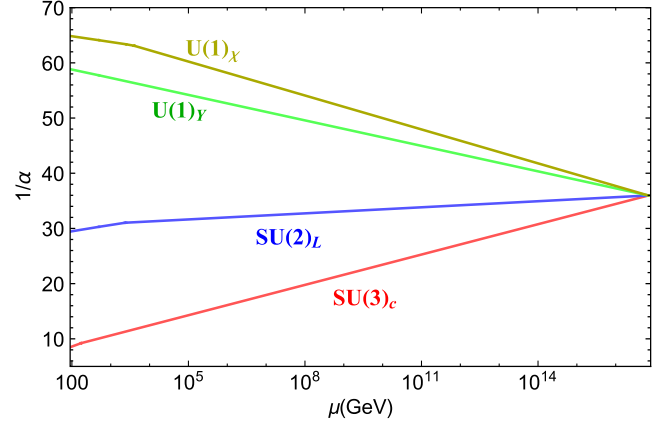


FIG. 1. Running of $1/\alpha_i$ with energy scale.

$1/\alpha_L$, and $1/\alpha_C$ are depicted as functions of energy scale in Fig. 1.

The symmetry breaking of $SU(2)_L \times U(1)_Y \times U(1)_\chi$ occurs through the VEVs $v_{\chi,1,2}$ of $\zeta \sim (0, 0, -10)$, $\phi_1^0 \sim (1/2, -1/2, -2)$, and $\phi_2^0 \sim (-1/2, 1/2, 2)$, where the values of (I_{3L}, Y, Q_χ) for each are shown. As a result, the mass-squared matrix spanning (Z, Z_χ) is given by

$$\begin{aligned} \mathcal{M}_{Z, Z_\chi}^2 &= \begin{pmatrix} (g_Z^2/2)(v_1^2 + v_2^2) & -(g_Z g_\chi / \sqrt{10})(v_1^2 + v_2^2) \\ -(g_Z g_\chi / \sqrt{10})(v_1^2 + v_2^2) & 5g_\chi^2 v_\chi^2 + (g_\chi^2/5)(v_1^2 + v_2^2) \end{pmatrix}. \end{aligned} \quad (29)$$

Using $M_{Z_\chi} = 4.1$ TeV from the LHC lower bound, the $Z - Z_\chi$ mixing is then at most

$$\theta_{Z-Z_\chi} \simeq \sqrt{\frac{2}{5}} \frac{g_\chi}{g_Z} \left(\frac{M_Z}{M_{Z_\chi}} \right)^2 = 1.85 \times 10^{-4}, \quad (30)$$

which is consistent with precision electroweak measurements [17].

VI. TWO VARIATIONS WITH DIRAC NEUTRINOS

Instead of the canonical scenario with Majorana neutrinos from the seesaw mechanism, the $U(1)_\chi$ extension allows for two interesting variations with Dirac neutrinos.

(A) Replace the scalar $\zeta \sim (1, -10)$ from the 126 by the scalar $\zeta' \sim (1, -5)$ from the 16. Now $\langle \zeta' \rangle \neq 0$ breaks $U(1)_\chi$ but $\nu^c \sim (1, -5)$ cannot obtain a Majorana mass. In fact, ζ' always appears together with $(\zeta')^*$. In other words, because of the chosen particle content, ζ' does not interact singly with any combination of the available fields. After spontaneous symmetry breaking, the resulting Higgs scalar $H_\chi = \sqrt{2}(\text{Re}(\zeta') - v_\chi)$ behaves as a particle with even R_χ even though its original Q_χ is odd.

In this scenario, both baryon number B and lepton number L are conserved, with Ω and Σ having $B = L = 0$, and S having $B = 0$ and $L = -1$. The Yukawa term $f_S S^* \nu^c \Sigma$ discussed earlier forms the link between them and the Dirac neutrinos. Again Σ^0 may be chosen as stable dark matter, because there can be no lighter collection of particles with an odd number of fermions carrying $B = L = 0$. Similarly, if S^0 is lighter than Σ^0 , then it is stable because there can be no lighter collection of particles with an even number of fermions carrying $B = 0$ and $L = -1$. The origin of dark matter is again $U(1)_\chi$ which allows B and L to be generalized to include dark matter.

(B) On top of $\zeta \sim (1, -10)$ from the 126 of $SO(10)$, add the scalar $\zeta'' \sim (1, 15)$ from the 672. Let the $U(1)_\chi$ symmetry be broken by the latter and not the former, i.e., $\langle \zeta'' \rangle = v_\chi$, but $\langle \zeta \rangle = 0$. In that case, there is again no Majorana mass term for ν^c , and neutrinos are Dirac fermions. However, there are now the allowed terms

$$\zeta^* \nu^c \nu^c, \quad \zeta^* S S. \quad (31)$$

They imply that ζ has $L = -2$ and S has $L = -1$. In other words, the proposal of Ref. [29] of leptonic dark matter S^0 with scalar dilepton mediator ζ is realized, where ζ decays only to two neutrinos. Assuming ζ to be light (10 to 100 MeV), the self-interacting dark matter S^0 may then explain [30] the central flatness of the density profile of dwarf galaxies [31]. On the other hand, ζ has a large production cross section through Sommerfeld enhancement at late times. Its decay to electrons and photons would disrupt [32] the cosmic microwave background (CMB) and be ruled out [33] by the precision observation data now available [34]. Here ζ decays only to neutrinos, thus solving this important problem. Note that if S is not a triplet but a singlet, then the Yukawa terms $\zeta'' S S S$ and $\zeta'' \zeta S$ would be allowed [29], in which case $U(1)_L$ breaks to Z_3 and S^* transforms as ζ , so it cannot be dark matter. As it is, the fact that $S \sim (1, 3, 0, -5)$ allows it to be stable dark matter, as well as a contributor to the gauge unification of $SU(5)$ from $SU(3)_C \times SU(2)_L \times U(1)_Y$.

VII. CONCLUDING REMARKS

It has been proposed in this paper that matter and dark matter are unified under $SO(10)$ which breaks to $SU(5) \times U(1)_\chi$ at $M_U \sim 7 \times 10^{16}$ GeV. Matter consists of fermions with odd Q_χ charge under $U(1)_\chi$ and bosons with even Q_χ . It encompasses all particles of the SM (extended to include two Higgs doublets) as well as the $U(1)_\chi$ gauge boson Z_χ and the corresponding Higgs singlet which breaks $U(1)_\chi$. Dark matter consists of fermions with even Q_χ and scalars with odd Q_χ . To achieve $SU(5)$ gauge unification from $SU(3)_C \times SU(2)_L \times U(1)_Y$, they are chosen to be a colored fermion octet $\Omega \sim (8, 1, 0, 0)$, an electroweak fermion

triplet $\Sigma \sim (1, 3, 0, 0)$, and a complex electroweak scalar triplet $S \sim (1, 3, 0, -5)$ at or below the TeV scale. The dark parity $R_\chi = (-1)^{Q_\chi + 2j}$ is identified as the stabilizing symmetry for dark matter. Either Σ^0 or S^0 (whichever is lighter) is a good dark-matter candidate.

In the canonical scenario, neutrinos are Majorana with $U(1)_\chi$ broken by the scalar singlet $\zeta \sim (1, -10)$ under $SU(5) \times U(1)_\chi$. However, if $\zeta' \sim (1, -5)$ or $\zeta'' \sim (1, 15)$ is used, neutrinos could be Dirac, and in the latter case, ζ itself may be the light scalar dilepton mediator for the self-interacting dark matter S^0 . Since ζ decays only to two neutrinos, it does not disrupt the CMB, unlike other models where the mediator decays to electrons and photons.

To verify this proposal that $U(1)_\chi$ is the origin of dark matter, the production of Z_χ would be a necessary first step. However, its mass is not precisely predicted, only that it should be at the TeV scale. At present, the LHC bound [13,14] is about 4.1 TeV. However, a more detailed study [35] shows that it can be improved. Other new particles to look for are the bound states of Ω , i.e., gluinonia, which are possible [25] with higher luminosity at the LHC.

It should also be pointed out that if supersymmetry is imposed on $SO(10) \rightarrow SU(5) \times U(1)_\chi$, then the origin of R parity is again traced to Q_χ . In other words, there is no need to impose it to distinguish the would-be identical Higgs and lepton superfields in the minimal supersymmetric standard model, because they now have different Q_χ . Hence it could turn out that supersymmetry is there after all, but to explain dark matter, $U(1)_\chi$ is still the key. In that case, gauge coupling unification comes about from the presence of the gluino (acting as Ω), the wino (acting as Σ), the bino, and two Higgsino doublets (replacing S), as well as complete multiplets of squarks and sleptons.

As remarked earlier, there are three equivalent markers of dark matter: $(-1)^{3(B-L)+2j}$, $(-1)^{Q_\chi+2j}$, and $(-1)^{Q_\psi+2j}$. They are all even for the known SM particles and odd for would-be particles of the dark sector. The choice of the latter is somewhat arbitrary and many studies have been made. In Ref. [3], $(-1)^{3(B-L)}$ was considered in the context of supersymmetry and $SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ was advocated but not $SO(10) \rightarrow SU(5) \times U(1)_\chi$, although $SU(5)$ by itself was discussed and discarded. Subsequent work all follow this lead. In Refs. [4,5], supersymmetric $SO(10)$ was considered with conserved $(-1)^{3(B-L)}$. The dark sector consists of all superpartners of the SM particles and the various Higgs multiplets used to break the symmetry at various scales. In Ref. [6], the scalar singlet and electroweak doublet contained in the 16 of $SO(10)$ are considered as dark matter in a nonsupersymmetric context. In Ref. [7], $SO(10) \rightarrow SU(5) \times (-1)^{Q_\chi}$ was considered. This work is closest to the present proposal, but there Z_χ is superheavy and unobservable, whereas here the SM particles have Q_χ

charges and couple to Z_χ at the TeV scale. Also, the chosen dark sector is completely different. In Ref. [8], nonsupersymmetric $SO(10)$ was considered using $(-1)^{3(B-L)}$ as a marker, but $U(1)_\chi$ was not mentioned and Z_χ is explicitly absent. However, this model is close to the present proposal in its dark-matter content, i.e., the electroweak fermion triplet Σ . In Refs. [9,10], nonsupersymmetric $SO(10)$ was considered with various breaking scales. There is again no Z_χ and the scenarios for dark matter are different. In Ref. [11], nonsupersymmetric $SO(10) \rightarrow SU(5) \times U(1)_\chi$ was mentioned but it breaks to the SM at the unification scale. Hence Z_χ is again superheavy. The dark sector mimics those of supersymmetry, i.e., the gauginos and the higgsinos. In Ref. [12], nonsupersymmetric $SO(10)$

was considered, where fermions in a vectorlike $\underline{10}_L + \underline{10}_R$ of $SO(10)$ belong to the dark sector. These are analogs of the Higgsinos in supersymmetry, i.e., the fermionic partners of the scalar $\underline{10}$ of $SO(10)$ which contains the Higgs bidoublet.

In summary, these references are related but also very different from the scenario discussed in this paper, which is indeed new and not contained in any previous study of this specific topic.

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