Matter parity as the origin of scalar dark matter

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We extend the concept of matter parity $P_M = (-1)^{3(B-L)}$ to nonsupersymmetric theories and argue that P_M is the natural explanation to the existence of dark matter of the Universe. We show that the nonsupersymmetric dark matter must be contained in a scalar **16** representation(s) of $SO(10)$, thus the unique low-energy dark matter candidates are P_M-odd complex scalar singlet(s) S and an inert scalar doublet(s) H_2. We have calculated the thermal relic dark matter (DM) abundance of the model and shown that its minimal form may be testable at LHC via the standard model (SM) Higgs boson decays $H_1 \to$ DM DM. The PAMELA anomaly can be explained with the decays DM $\to \nu l W$ induced via seesawlike operator which is additionally suppressed by the Planck scale. Because the SM fermions are odd under matter parity too, the DM sector is just our scalar relative.

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I. INTRODUCTION

While the existence of dark matter (DM) of the Universe is now established without doubt [1], its origin, nature, and properties remain obscured. Any well motivated theory beyond the standard model (SM) must explain what constitutes the DM and why those DM particles are stable. In most popular models beyond the SM, such as the minimal supersymmetric SM, additional discrete Z_2 symmetry is imposed by hand to ensure the stability of the lightest Z_2-odd particle. There is no known general physics principle for the origin of DM which could discriminate between the proposed DM models.

In this paper, we propose that there actually might exist such a common physics principle for the theories of DM. It follows from the underlying unified symmetry group for all matter fields in grand unified theories (GUTs) and does not require supersymmetry. One can classify all matter fields in nature under the discrete remnant of the GUT symmetry group, which is nothing but the matter parity P_M. Thus the existence of DM might be a general property of nature rather than an accidental outcome of some particular model. As a general result, there is no "dark world" decoupled from us, rather we are part of it as the SM fermions are also odd under the matter parity P_M.

We argue that, assuming $SO(10)$ [2] to be the GUT symmetry group, the discrete center Z_n of $U(1)_X \in SO(10)$ remains unbroken. For the simplest case, $n = 2$, the GUT symmetry breaking chain $SO(10) \to SU(5) \times P_M$ implies that all the fermion and scalar fields of the GUT theory, including the SM particles plus the right-handed neutrinos N_i, carry well-defined discrete quantum numbers which are uniquely determined by their original representation under $SO(10)$. We show that nonsupersymmetric DM candidates can come only from **16** scalar representations of $SO(10)$, and the unique low-energy DM fields are a new $SU(2)_L \times U(1)_Y$ P_M-odd scalar doublet(s) H_2 [3] and singlet(s) S [4,5].

We formulate and study the minimal matter parity induced phenomenological DM model which contains one inert doublet H_2 and one complex singlet S. We show that the observed DM thermal freeze-out abundance can be achieved for a wide range of model parameters. We also show that the PAMELA [6] and ATIC [7] anomalies in $e^+/(e^- + e^+)$ and $e^- + e^+$ cosmic ray fluxes can be explained by DM decays via $d = 6$ [8] operators. In our case, the Planck scale suppressed P_M-violating seesawlike operator is of the form $m/(\Lambda_N M_P) LLH_1H_2$, where m/M_P is P_M-violating heavy neutrino mixing. In this model, the SM Higgs boson H_1 is the portal [9] to the DM. We show that for the well motivated model parameter, the DM abundance predicts the decay $H_1 \to$ DM DM, which allows one to test the model at LHC [10].

II. MATTER PARITY AS THE ORIGIN OF DM

The prediction of $SO(10)$ GUT is that the fermions of every generation form one $SO(10)$ multiplet $\mathbf{16_i}$, $i = 1, 2, 3$. This is in perfect agreement with experimental data as there exist 15 SM fermions per generation plus right-handed N_i for the seesaw mechanism [11]. Assuming $SO(10)$ GUT, the first step in the group theoretic branching rule for the GUT symmetry breaking,

$$SO(10) \to SU(5) \times U(1)_X \to SU(5) \times Z_2, \quad (1)$$

implies that every $SU(5)$ matter multiplet [12] and N_i carry an additional uniquely defined quantum number under the $U(1)_X$ symmetry. The $U(1)_X$ symmetry can be further broken to its discrete subgroup Z_n by an order parameter carrying n charges of X [13,14]. The simplest case Z_2, which allows for the seesaw mechanism induced by the heavy neutrinos N_i [11], yields the new parity P_X with the field transformation $\Phi \to \pm\Phi$. Therefore, at the electroweak scale after $SU(5)$ symmetry breaking, the actual SM symmetry group becomes $SU(2)_L \times U(1)_Y \times P_X$. The discrete remnant of the GUT symmetry group, P_X, implies the existence of stable DM.

Under Pati-Salam charges $B - L$ and T_{3R} the X charge is decomposed as

$$X = 3(B - L) + 4T_{3R}, \quad (2)$$

while the orthogonal combination, the SM hypercharge Y, is gauged in $SU(5)$. Because X depends on $4T_{3R}$ which is always an even integer for $T_{3R} = 1/2, 1, \ldots$, the Z_2 X parity of a multiplet is determined by $3(B - L) \bmod 2$. Therefore one can write

$$P_X = P_M = (-1)^{3(B-L)}, \quad (3)$$

and identify P_X with the well-known matter parity [15], which is equivalent to R parity in supersymmetry. While $U(1)_X$, $X = 5(B - L) - 2Y$, has been used to discuss and to forbid proton decay operators [16], so far the parity (3) has been associated only with supersymmetric phenomenology.

Because of Eq. (1), a definite matter parity P_M is the general intrinsic property of every matter multiplet. The decomposition of **16** of $SO(10)$ under (1) is $\mathbf{16} = \mathbf{1}^{16}(5) + \bar{\mathbf{5}}^{16}(-3) + \mathbf{10}^{16}(1)$, where the $U(1)_X$ quantum numbers of the $SU(5)$ fields are given in brackets. This implies that under the matter parity, all of the fields $\mathbf{10}^{16}$, $\bar{\mathbf{5}}^{16}$, $\mathbf{1}^{16}$ are odd. At the same time, all other fields coming from small $SO(10)$ representations, **10**, **45**, **54**, **120**, and **126**, are predicted to be even under P_M. Thus the SM fermions belonging to $\mathbf{16}_i$ are all P_M odd while the SM Higgs boson doublet is P_M even because it is embedded into $\mathbf{5}^{10}$ and/or $\bar{\mathbf{5}}^{10}$, and $\mathbf{10} = \mathbf{5}^{10}(-2) + \bar{\mathbf{5}}^{10}(2)$. Although $B - L$ is broken in nature by heavy neutrino Majorana masses, $(-1)^{3(B-L)}$ is respected by interactions of *all* matter fields.

As there is no DM candidate in the SM, we have to extend the particle content of the model by adding new $SO(10)$ multiplets. The choice is *unique* as only **16** contains P_M-odd particles. Adding a new fermion **16** is equivalent to adding a new generation, and this does not give DM. Thus we have only one possibility, the scalar(s) **16** of $SO(10)$. Because DM must be electrically neutral, **16** contains only two DM candidates. Under $SU(2)_L \times U(1)_Y$ those are the complex singlet $S = \mathbf{1}^{16}$ and the inert doublet $H_2 \in \bar{\mathbf{5}}^{16}$.

III. DM PREDICTIONS OF THE MINIMAL MODEL

GUT symmetry groups are known to be very useful for classification of particle quantum numbers, and this is sufficient for predicting the DM candidates. Unfortunately, GUTs fail, at least in their minimal form, to predict correctly coupling constants between matter fields. Therefore we cannot trust GUT model building for predicting details of DM phenomenology. Instead we study the *phenomenological low-energy* Lagrangian for the SM Higgs H_1 and the P_M-odd scalars S and H_2,

$$\begin{aligned} V = {} & -\mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 + \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 \\ & + \lambda_{SH_1} (S^\dagger S)(H_1^\dagger H_1) + \mu_2^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2 \\ & + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \frac{\lambda_5}{2}[(H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2] + \frac{b_S^2}{2}[S^2 + (S^\dagger)^2] \\ & + \lambda_{SH_2} (S^\dagger S)(H_2^\dagger H_2) + \frac{\mu_{SH}}{2}[S^\dagger H_1^\dagger H_2 + S H_2^\dagger H_1], \end{aligned} \quad (4)$$

which respects $H_1 \to H_1$ and $S \to -S$, $H_2 \to -H_2$. The doublet terms alone form the inert doublet model [3]. Following Ref. [5], to ensure $\langle S \rangle = 0$, we allow only the soft mass terms b_S, μ_{SH}, and the λ_5 term to break the internal $U(1)$ of the odd scalars. Thus the singlet terms in (4) alone form the model A2 of [5]. The two models mix via λ_{SH}, μ_{SH} terms. Notice that mass-degenerate scalars are strongly constrained as DM candidates by direct searches for DM. The λ_5, b_S^2, and μ_{SH} terms in Eq. (4) are crucial for lifting the mass degeneracies.

We stress that our model of DM is based on the particle quantum numbers and does not rely on numerology. However, the phenomenological studies of the model necessarily raise questions such as the gauge coupling unification. The one-loop β functions for gauge couplings g, g', and g_3 are given by $\beta_{g'} = 7g'^3$, $\beta_g = -3g^3$, and $\beta_{g_3} = -7g^3$. Based solely on the running due to those beta functions, we identify the unification scale 2×10^{16} GeV by the solution for $g_2 = g_3$. The exact values of gauge couplings at M_G are given by $g_1 = \sqrt{5/3}g' = 0.58$, $g_2 = g_3 = 0.53$. The precision of unification of all three gauge couplings in our model is better than in the SM because of the existence of an extra scalar doublet. We assume that an exact unification can be achieved due to the GUT threshold corrections in full $SO(10)$ theory, which we cannot estimate because the details of GUT symmetry breaking are not known [17]. In the minimal model with one extra doublet, the required change of g_1 at the GUT scale due to the threshold corrections is 10%. If, for example, there is one DM scalar multiplet for each generation of fermions, the required threshold corrections are smaller, at the level of 4%.

In the following we assume that DM is a thermal relic and calculate its abundance using the MICROMEGAS package [18]. The DM interactions (4) were calculated using the FEYNRULES package [19]. To present numerical examples, we fix the doublet parameters following Ref. [20] as $m_{A_0} - m_{H_0} = 10$ GeV, $m_{H^\pm} - m_{H_0} = 50$ GeV and treat m_{H_0} and μ_2 as free parameters. For predominantly singlet DM, we present in Fig. 1 the allowed 3σ regions in the $m_S^2 = \mu_S^2 + \lambda_{SH_1} v^2/2 - b_S^2$ and λ_{SH_1} plane for $b_S = 5$ GeV, $m_{H_0} = 450$ GeV and the values of μ_{SH} as indicated in the figure. For comparison, we also plot the corresponding prediction of the real scalar model. For those parameters, the observed DM abundance

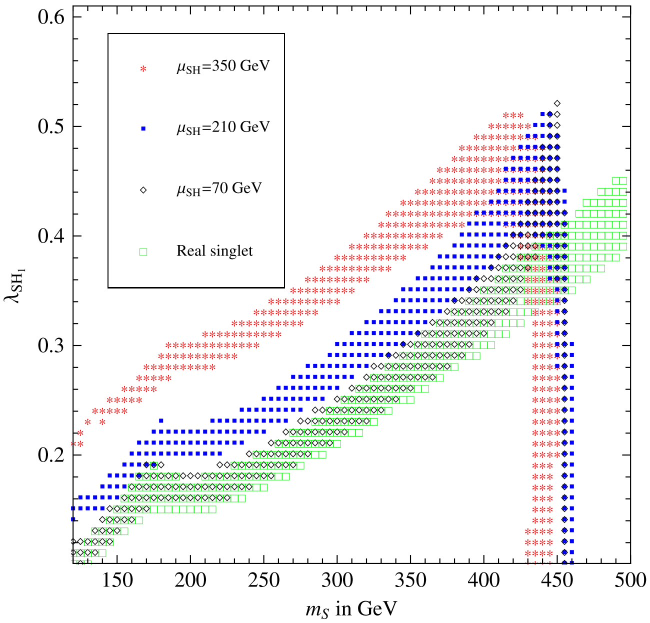

FIG. 1 (color online). Allowed 3σ regions for predominantly singlet DM in the (m_S, λ_{SH_1}) plane for $b_S = 5$ GeV, $m_{H_0} = 450$ GeV.

can be obtained for $m_S < m_{H_0}$. Because of the mixing parameter μ_{SH}, a large region in the (m_S, λ_{SH_1}) plane becomes viable.

To study DM dependence on doublet parameters we present in Fig. 2 the (m_{H_0}, μ_2) parameter space for which the observed DM abundance can be obtained. Values of the singlet mass are presented by the color code and we take $\mu_{SH} = 0$, $b_S = 5$ GeV. Without singlet S, in the inert doublet model [20], the allowed parameter space is the narrow region on the diagonal of Fig. 2 starting at $m_{H_0} \approx 670$ GeV. In our model much larger parameter space becomes available.

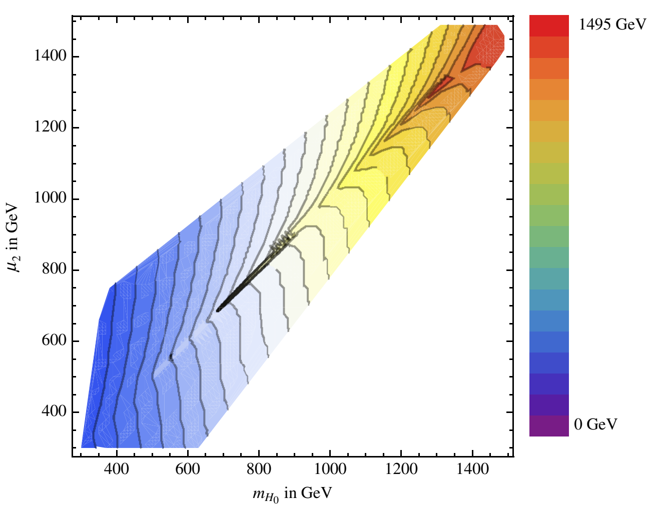

FIG. 2 (color online). Allowed (m_{H_0}, μ_2) parameter space for $\mu_{SH} = 0$ and different values of m_S represented by the color code.

IV. PAMELA, ATIC, AND FERMI DATA

The PAMELA satellite has observed a steep rise of $e^+/(e^- + e^+)$ cosmic ray flux with energy and no excess in the $\bar{p}/p$ ratio [6]. The ATIC experiment claims a peak in $e^- + e^+$ cosmic ray flux around 700 GeV [7], a claim that will be checked by the FERMI satellite soon. To explain the cosmic e^+ excess with annihilating DM requires enhancement of the annihilation cross section by a factor 10^{3-4} compared to what is predicted for a thermal relic. Nonobservation of photons associated with annihilation [21] and the absence of hadronic annihilation modes [22] constrains this scenario very strongly. However, the PAMELA anomaly can also be explained with decaying thermal relic DM with lifetime 10^{26} s [23], 3-body decays in our case.

In our scenario, the global Z_2 matter parity can be broken by Planck scale effects [13]. If there exists, at Planck scale, a $SO(10)$ fermion singlet N', its mixing with the $SU(5)$ P_M-odd singlet neutrinos N via a mass term mNN' breaks P_M explicitly but softly. The exchange of N now induces also a seesawlike [11] operator

$$\frac{\lambda_N}{M_N}\frac{m}{M_P}LLH_1H_2 \to 10^{-30}\ \text{GeV}^{-1}\nu l^- W^+ H_2^0, \quad (5)$$

where we have taken $\lambda_N \sim 1$, $M_N \sim 10^{14}$ GeV, and $m \sim v \sim 100$ GeV. Such a small effective Yukawa coupling explains the long DM lifetime 10^{26} s.

V. LHC PHENOMENOLOGY

In our scenario, the DM couples to the SM only via the Higgs boson couplings Eq. (4). Therefore, discovering ~1 TeV DM particles at LHC is very challenging. However, if DM is relatively light, the SM Higgs decays $H_1 \to$ DM DM become kinematically allowed and the SM Higgs branching ratios are strongly affected. Such a scenario has been studied by LHC experiments [10] and can be used to discover light scalars.

In our model, such a scenario is realized for $\mu_S = 0$, small $b_S \ll v$, and heavy doublet. In this case, the DM is predominantly a split singlet and, in addition, the DM abundance relates the DM mass $m_S^2 \approx \lambda_{SH_1} v^2/2 - b_S^2$ to the SM Higgs boson mass m_{H_1}, as seen in Fig. 3. For $m_{H_1} = 120$ GeV, $b_S = 5$ GeV we predict $m_S = 48$ GeV with the Higgs branching ratios (BR) $\text{BR}(H_1 \to b\bar{b} + c\bar{c} + \tau\bar{\tau}) = 14.2\%$, $\text{BR}(H_1 \to \text{DM DM}) = 42.4\%$, and $\text{BR}(H_1 \to S_2 S_2) = 42.4\%$. The second heaviest singlet S_2 with the mass $m_{S_2}^2 \approx \lambda_{SH_1} v^2/2 + b_S^2$ decays via the SM Higgs exchange to $S_2 \to \text{DM}\mu\bar{\mu}$ or $S_2 \to \text{DM}c\bar{c}$ with almost equal branching ratios. Thus the SM Higgs boson decay modes are very strongly modified. This makes the H_1 discovery more difficult at LHC but, on the other hand, allows the scenario to be tested via the Higgs portal [9].

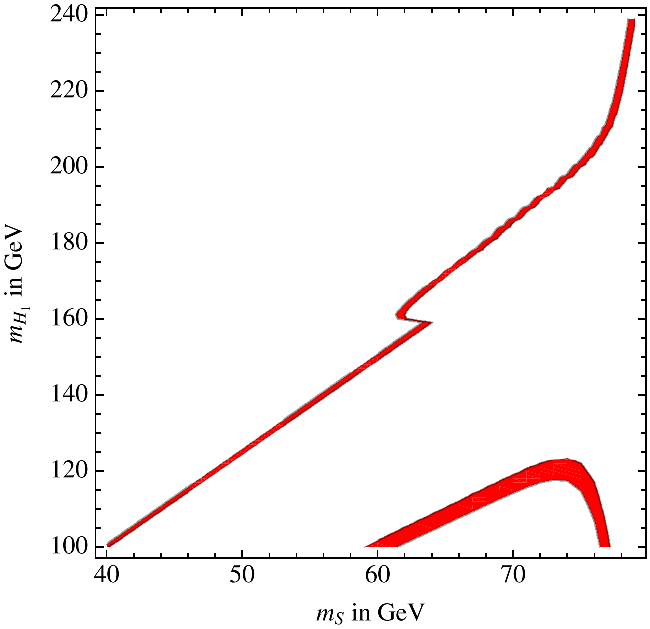

FIG. 3 (color online). Allowed 3σ regions in the singlet DM and SM Higgs boson mass plane for $\mu_S = 0$ and $b_S = 5$ GeV.

VI. CONCLUSIONS

We have extended the concept of Z_2 matter parity, $P_M = (-1)^{3(B-L)}$, to nonsupersymmetric GUTs and argued that P_M gives the natural origin of DM of the Universe. Assuming that $SO(10)$ is the GUT symmetry group, the matter parity of all matter multiplets is determined by their $U(1)_X$ charge under Eq. (1). Consequently, the nonsupersymmetric DM must be contained in the scalar representation **16** of $SO(10)$. This implies that the theory of DM becomes completely predictive and the only possible low-energy DM candidates are the P_M-odd scalar singlet(s) S and doublet(s) H_2. We have calculated the DM abundances in the minimal DM model and show that it has a chance to be tested at LHC via the Higgs portal. Planck-suppressed P_M breaking effects may occur in the heavy neutrino sector leading to decays DM $\to \nu l W$ which can explain the PAMELA and FERMI anomalies.

Our main conclusion is that there is nothing unusual in the DM which is just scalar relative of the SM fermionic matter. Although $B - L$ is broken in nature by heavy neutrino Majorana masses, $(-1)^{3(B-L)}$ is respected by interactions of all matter fields implying stable scalar DM.

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