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 non-supersymmetric theories and argue that $P_M$ is the natural explanation to the existence of Dark Matter of the Universe. We show that the non-supersymmetric Dark Matter must be contained in 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 inert scalar doublet(s) $H_2$. We have calculated the thermal relic Dark Matter abundance of the model and shown that its minimal form may be testable at LHC via the SM Higgs boson decays $H_1 \rightarrow DM DM$. The PAMELA anomaly can be explained with the decays $DM \rightarrow \nu W^*$ induced via seesaw-like operator which is additionally suppressed by Planck scale. Because the SM fermions are odd under matter parity too, the DM sector is just our scalar relative.

Introduction. While the existence of Dark Matter (DM) of the Universe is now established without doubt [1], its origin, nature and properties remain obscure. 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 Letter 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 $SO(10) \rightarrow SU(5) \times P_M$ 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 non-supersymmetric DM candidates can come only from 16 scalar representations of $SO(10)$, and the unique low energy DM fields are new $SU(2)_L \times U(1)_Y \times P_M$-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 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 seesaw-like operator is of the form $m/(\Lambda_N M_P)LLH_1 H_2$, 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 well motivated model parameter the DM abundance predicts the decay $H_1 \rightarrow DM DM$, which allows to test the model at LHC [10].

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 $16_i$, $i = 1, 2, 3$. This is in a 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,

\[ SO(10) \rightarrow SU(5) \times U(1)_X \rightarrow SU(5) \times Z_2, \tag{1} \]

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 $\Phi \rightarrow \pm \Phi$. 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

\[ X = 3(B-L) + 4T_{3R}, \tag{2} \]

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 $3(B - L) \mod 2$. Therefore one can write
\[
P_X = P_M = (-1)^3(B-L),
\]
and identify $P_X$ with the well known matter parity \cite{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 \cite{10}, so far the parity \cite{3} has been associated only with SUSY phenomenology.

Due to 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 $16 = 1^{16}(5) + 5^{16}(3) + 10^{16}(1)$, where the $U(1)_X$ quantum numbers of the $SU(5)$ fields are given in brackets. This implies that under the matter parity all the fields $10^{16}, 5^{16}, 1^{16}$ are odd. At the same time, all other fields coming from small $SO(10)$ representations, $10, 45, 54, 120$ and $26$, are predicted to be even under $P_M$. Thus the SM fermions belonging to $16$, are all $P_M$-odd while the SM Higgs boson doublet is $P_M$-even because it is embedded into $5^{10}$ and/or $5^{10}$, and $10 = 5^{10}(-2) + 5^{10}(2)$. 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 $S = 1^{16}$ and the inert doublet $H_2 = 5^{16}$.

**DM predictions for 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 *phenomenological low-energy* Lagrangian for the SM Higgs $H$ and the $P_M$-odd scalars $S$ and $H_2$,
\[
V = -\mu_S^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 + \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 \\
+ \lambda_{SH}(S^\dagger S)(H_1^\dagger H_1) + \mu_S^2 H_2^\dagger H_2 + \lambda_2 (H_2^\dagger H_2)^2 \\
+ \lambda_3 (H_1^\dagger H_1)(H_1^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\
+ \frac{\lambda_5}{2} \left[ (H_1^\dagger H_1)^2 + (H_2^\dagger H_2)^2 \right] + \frac{\lambda_6}{2} \left[ S^2 + (S^\dagger S)^2 \right] \\
+ \lambda_{SH}(S^\dagger S)(H_2^\dagger H_2) + \frac{\mu_{SH}}{2} \left[ S^\dagger H_1^\dagger H_2 + S H_2^\dagger H_1 \right],
\]
which respects $H_1 \rightarrow H_1$ and $S \rightarrow -S, H_2 \rightarrow -H_2$. The doublet terms alone form the inert doublet model \cite{3}. Following Ref. [5], to ensure $\langle S \rangle = 0$, we allow only the soft mass terms $b_S, \mu_{SH}$ and the $\lambda_5$ term to break the internal $U(1)$ of the odd scalars. Thus the singlet terms in (1) alone form the model $\Delta 2$ of [5]. The two models mix via $\lambda_{SH}, \mu_{SH}$ terms. Notice that mass-degenerate scalars are strongly constrained as DM candidates by direct searches for DM. The $\lambda_5, b_2^2$ and $\mu_{SH}$ 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 rise questions such as the gauge coupling unification. The one-loop $\beta$-functions for gauge couplings $g, g'$ and $g_3$ are given by $\beta_g = 7g^3$, $\beta_{g'} = -3g^3$ and $\beta_{g_3} = -7g_3^3$. Based solely on the running due to those beta functions, we identify the unification scale $2 \times 10^{16}$ GeV by therosolution $g_2 = g_3$. The exact values of gauge couplings at $M_G$ are given by $g_1 = \sqrt{5/3}g'_1 = 0.58$, $g_2 = g_3 = 0.53$. 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 thresholds corrections in full $SO(10)$ theory which we cannot estimate because the details of GUT symmetry breaking are not known \cite{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 MicrOMEGAs package \cite{18}. The DM interactions (4) were calculated using FeynRules package \cite{19}. To present numerical examples we fix the doublet parameters following Ref. \cite{20} as $m_{A_0} - m_{H_0} = 10$ GeV, $m_{H^\pm} - m_{H_0} = 50$ GeV and treat $m_{H_0}$ and $\mu_2$ as free parameters. For predominantly sin-
nlet DM we present in Fig. 1 the allowed 3σ regions in the $m_S^2 = \mu_S^2 + \lambda_{SH} v^2/2 - b_S^2$ and $\lambda_{SH1}$ plane for $b_S = 5$ GeV, $m_{H_0} = 450$ GeV and the values of $\mu_{SH}$ as indicated in the figure. For comparison we also plot the corresponding prediction of the real scalar model (light green band). For those parameters the observed DM abundance can be obtained for $m_S < m_{H_0}$. Due to the mixing parameter $\mu_{SH}$, a large region in the $(m_S, \lambda_{SH1})$ plane becomes viable.

To study DM dependence on doublet parameters we present in Fig. 2 the $(m_{H_0}, \mu_2)$ parameter space for which the observed DM abundance can be obtained. Values of the singlet mass are presented by the colour code and we take $\mu_{SH} = 0$, $b_2 = 5$ 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.

**PAMELA, ATIC and FERMI data.** PAMELA satellite has observed steep rise of $e^+/e^- + e^+$ cosmic ray flux with energy and no excess in $p/p$ ratio [6]. ATIC experiment claims a peak in $e^- + e^+$ cosmic ray flux around 700 GeV [7], a claim that will be checked by FERMI satellite soon. To explain the cosmic $e^+$ excess with annihilating DM requires enhancement of the annihilation cross section by a factor $10^{-4}$ compared to what is predicted for a thermal relic. Non-observation 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 seesaw-like [11] operator

$$\lambda_N \frac{m}{M_N} LLH_1 H_2 \rightarrow 10^{-30} \text{GeV}^{-1} \nu^l W^+ H_2^0,$$

(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.

**LHC phenomenology.** In our scenario the DM couples to the SM only via the Higgs boson couplings Eq. (4). Therefore, discovering $\sim 1$ TeV DM particles at LHC is very challenging. However, if DM is relatively light the SM Higgs decays $H_1 \rightarrow DM DM$ 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 split singlet and, in addition, the DM abundance relates the DM mass $m_{S_2}^2 \approx \lambda_{SH1} v^2/2 - b_S^2$ 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 $BR(H_1 \rightarrow bb + c\bar{c} + \tau\bar{\tau}) = 14.2\%$, $BR(H_1 \rightarrow DM DM) = 42.4\%$ and $BR(H_1 \rightarrow S_2 S_2) = 42.4\%$. The second heaviest singlet $S_2$ with the mass $m_{S_2}^2 \approx \lambda_{SH1} v^2/2 + b_S^2$ decays via the SM Higgs exchange to $S_2 \rightarrow DM \mu\bar{\mu}$ or $S_2 \rightarrow DM e\bar{e}$ 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].

**Conclusions.** We have extended the concept of $Z_2$ matter parity, $P_M = (-1)^{3(B-L)}$, to non-supersymmetric 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 non-supersymmetric 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 shown that it has a chance to be tested at LHC via Higgs portal. Planck-suppressed $P_M$ breaking effects may occur in the heavy neutrino sector leading to decays $DM \rightarrow \nu_l W$ 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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