ASYMMETRIC DARK MATTER VIA LEPTOGENESIS AND DARK SPHALERONS

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We discuss the generation of a dark matter asymmetry, via new sphaleron processes associated to an extra non-abelian gauge symmetry common to both the visible and the dark sectors. Such a theory can naturally produce an abundance of asymmetric dark matter which is of the same size as the lepton and baryon asymmetries, as suggested by the similar sizes of the observed baryonic and dark matter energy content, and provide a definite prediction for the mass of the dark matter particle. We discuss in detail a minimal realization in which the Standard Model is only extended by dark matter fermions which form “dark baryons” through an SU(3) interaction, and a (broken) horizontal symmetry that induces the new sphalerons. The dark matter mass is predicted to be $\sim 6$ GeV, close to the region favored by DAMA and CoGeNT. Furthermore, a remnant of the horizontal symmetry should be broken at a lower scale and can also explain the Tevatron dimuon anomaly.

1 Introduction

We now know that about 73% of the energy density of the Universe is in the form of dark energy and causes the accelerated expansion of the Universe while the remaining 27% is composed of matter. Baryonic matter makes up only 5%, while about five times as much is in the form of a non-luminous weakly interacting species, dubbed “Dark Matter” (DM). While this cosmological book-keeping is well developed, the particle nature of DM continues to be one of the most important open questions of particle physics. The most popular candidates for DM are weakly interacting massive particles (WIMPs). WIMPs arise naturally in theories, such as supersymmetry, which provide a solution to the hierarchy problem and include a “natural” DM candidate once a discrete symmetry, e.g., R-parity, is introduced, so that the least massive particle charged under the new symmetry is stable or very long lived. This kind of DM comes with the WIMP miracle, i.e., the correct interaction cross-section to thermally produce the density of DM in the early Universe. The same is true for extra-dimensional models where KK parity ensures the stability of the DM candidates. In this scenario, the closeness of the dark matter and baryonic energy densities is merely a coincidence, since they are produced by unrelated mechanisms. However, their similarity suggests that they originated from the same source. This is the case in models of asymmetric dark matter (ADM), a relatively old idea which has recently received a rising interest. In ADM models, the DM is made up of charge-neutral Dirac fermions, just like baryonic matter and unlike the SUSY neutralino which is a Majorana fermion. Thus, the DM we see today is not generated thermally in the early Universe, but through a particle-antiparticle asymmetry in its production mechanism tied to the production of ordinary matter, giving rise to similar number densities for ordinary matter and DM. Therefore, models of ADM often predict DM masses of $\mathcal{O}(1)$ GeV. The phenomenology
of ADM is therefore quite different from that of a thermal DM relic. In particular, the prospects of indirect detection of DM in these models are suppressed, since the DM does not annihilate if only an asymmetric component is present. Nevertheless, there could still be some indirect effects, such as the effect of accreting ADM in the core of stars\textsuperscript{11,12}.

Here we will summarize the study presented in Ref. \textsuperscript{13}, where the asymmetries in both baryons and DM are created simultaneously by the same processes, as suggested by their similar abundances. First, a lepton asymmetry from the decay of heavy right-handed neutrinos, as in leptogenesis\textsuperscript{14}, is induced and then this lepton number is partially converted into both baryon and DM numbers through new sphaleron processes which we will dub dark sphalerons. In order to achieve this, we will assume that there is an additional non-abelian gauge symmetry group $G$, under which both the DM sector and the SM fermions are charged. For definiteness, we will consider an additional $SU(2)$ symmetry, but other symmetry groups could also fulfill our purposes. This extra gauge symmetry could arise from some unified theory at higher scales, although this is not required. Apart from the right-handed neutrinos and the extra gauge symmetry (spontaneously broken by scalar SM singlets), we only need to introduce new fermion fields $X$, that are singlets under the SM gauge group but couple to the new gauge symmetry, and will provide the DM candidates.

We include a QCD-like gauge interaction for the DM fermions that prevents their mixing with neutrinos, ensuring their stability without any ad hoc discrete symmetry. The similarity with the SM QCD interaction is also suggestive, given the similar masses of baryons and DM required to fit the observed energy densities. As the DM is essentially composed of dark baryons, it scatters with itself through the QCD-like gauge interaction. This self-interaction can be quite large and leads to almost spherical DM halos in galaxies, in somewhat better agreement with data, compared to WIMPs\textsuperscript{15}. The current best limit on the interaction strength comes from observed ellipticities of DM halos of galaxies\textsuperscript{16}. However, limits from colliding galaxy clusters, though slightly weaker, are thought to be more robust. These observations tell us that the QCD-like gauge interaction cannot be much stronger than that between baryons.

2 The Model

We extend the SM gauge group with an additional $SU(2)_{H} \times SU(3)_{DC}$, where the $SU(2)_{H}$ is a gauged flavour symmetry (horizontal symmetry) introduced to provide the dark sphalerons. We have chosen an $SU(2)_{H}$ for the simplicity of the discussion but, in principle, other non-abelian gauge symmetries encompassing all three fermion generations could be considered as well to address the flavor puzzle. The additional dark color (DC) group $SU(3)_{DC}$ is a color-like gauge interaction in the dark sector. The DM candidate in this model is a charge neutral $SU(3)_{DC}$ baryon.

The fermionic field content in the model is given in Tab. 1 with the corresponding charges. Notice that the choice of which fermion generations form the $SU(2)_{H}$ doublets is arbitrary and only affects the constraints that can be set with present data on flavour changing neutral current (FCNC) processes on the scale at which the symmetry is broken, but not the generation of the baryon and DM asymmetries. In Tab. 1 the $SU(2)_{H}$ doublets are composed from the fermions of the first two generations, for which the present bounds are strongest, but other possibilities will be briefly discussed in Sec. 3. Notice that the only fermion singlet is the right-handed neutrino, for which a Majorana mass is allowed and will be assumed in order to have a see-saw mechanism\textsuperscript{17,18,19} for neutrino masses and a lepton number asymmetry in their decay that can seed baryon and DM asymmetry generation. Moreover, since the DM fermions are Dirac, we can define a global DM number $X$, that will be conserved at the Lagrangian level just as the baryon number $B$.

We further assume that the scalar sector is such that it can provide the required mass terms
Table 1: Fermion field content for our illustrative model and the corresponding charge assignments. Whenever a field has an index $a$, the model contains three copies of this field. Note that the assignment of putting particular generations in the SU(2)$_H$ doublets is arbitrary.

<table>
<thead>
<tr>
<th>Field</th>
<th>$Y$</th>
<th>$L$</th>
<th>$H$</th>
<th>$C$</th>
<th>$DC$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{La} (v_{aL}, \ell_{aL})$</td>
<td>$-$1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$L_R (\epsilon_R, \nu_R)$</td>
<td>$-$1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\tau_R$</td>
<td>$-$1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\nu_{aR}$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$Q_{aL} (u_{aL}, d_{aL})$</td>
<td>1</td>
<td>6</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$Q_R (u_R, c_R)$</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$Q_{R}^H (d_R, s_R)$</td>
<td>$-$1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$t_R$</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$b_R$</td>
<td>$-$1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$X_{H} (x_R^H, x_R^H)$</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$x_R^H, x_R^H$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

for the fermions, either directly or through higher-dimensional operators, after the breaking of both, the electroweak and the SU(2)$_H$ symmetries. For instance, a minimal realization consists of an extra SU(2)$_H$ doublet, besides the SM Higgs, with Yukawa couplings given in terms of effective $d = 5$ operators such as

$$O_{d=5} = c_a \bar{L}_H \Phi_H \Phi_L L_{La}$$

where $\Phi_H L$ is the SU(2)$_H L$ Higgs. After breaking of the SU(2)$_H$ symmetry, this reproduces the SM Yukawa terms. Just like the $d = 5$ Weinberg operator for neutrino masses, such operators can be generated in several different ways. The relevant phenomenological aspects of the model are independent of the scalar sector, so we shall not discuss it in more detail.

In this model, which is free of gauge anomalies, dark sphalerons satisfy $\Delta B = \Delta X = \Delta L$, while the SM sphalerons satisfy $\Delta B = \Delta L$ as usual, resulting in an overall conservation of $B - X - L$ at scales where both sphalerons are active and conservation of both $B - L$ and $X$ separately in the intermediate regime, where only the dark sphalerons are turned off. Thus, if an initial $L$ asymmetry is produced in the decay of the heavy Majorana right-handed neutrinos, both kinds of sphalerons will try to erase it. However, since $B - X - L$ is exactly conserved by the combination of both sphalerons, net $B$ and $X$ asymmetries will be induced. In order to obtain the precise ratios between the final $B$, $L$ and $X$ asymmetries the equilibrium equations for the chemical potentials have to be written down. For the final DM to baryon ratio, we obtain

$$\frac{X}{B} \rightarrow -\frac{11}{14}$$

Therefore, in order to accommodate the observed values of $\Omega_X$ and $\Omega_B$, we must have

$$m_{DM} \simeq m_B \frac{14 \Omega_X}{11 \Omega_B} = 5.94 \pm 0.42 \text{ GeV}$$

including the errors of the WMAP7 measurements. This value is in the low mass regime between 5 and 10 GeV favored by the claimed DM signals of the DAMA/LIBRA$^{20}$ and CoGeNT$^{21}$ collaborations. In particular it is strikingly close to the $\sim 7$ GeV required to consistently describe both signals and is within the 99% confidence level for the mass obtained in Ref.$^{22}$. 

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3 Constraints and phenomenological prospects

The first requisite that has to be met for successful generation of the baryon and dark matter asymmetries via leptogenesis, is that the $SU(2)_H$ sphalerons reach thermal equilibrium before the phase transition occurs and suppresses their rate. Thus, the sphaleron rate should be greater than the Hubble rate, leading to a lower bound on the $SU(2)_H$ coupling constant as a function of the temperature above which equilibrium should be achieved:

$$\alpha_H^4 = \left(\frac{g_H^2}{4\pi}\right)^4 \gtrsim 10\frac{T}{M_{Pl}}$$  (4)

On the other hand, a lower bound on the strength of the $SU(2)_H$ interaction at lower energies can be derived from the requirement that the thermally produced symmetric component of dark matter is transferred to the SM fast enough. Indeed, as with any field which is kept in thermal equilibrium, the ADM candidate will have a thermal abundance of both particles and antiparticles in the early Universe. In order for the DM to become asymmetric, there must exist interactions through which this symmetric thermal abundance can be effectively annihilated once the ADM falls out of thermal equilibrium. In our example model, this is achieved by the strong $SU(3)_{DC}$ interactions connecting the symmetric part of the DM fields into dark $SU(3)_{DC}$ mesons which can decay to SM particles via $SU(2)_H$ gauge bosons. Analogously to pion decays in the SM, the dark meson decays will require a chirality flip of the SM fermions they decay into. To estimate the decay rate of the dark mesons we will assume that the dominant decay channel is either to two muons or a tau and a lighter lepton and thus proportional to the muon or tau mass.

In order not to disturb the standard history of the Universe, the $SU(3)_{DC}$ mesons (which constitute a large matter component) must decay sufficiently fast into SM fermions so that they are no longer present during big bang nucleosynthesis (BBN). Thus, the lifetime of the mesons must be significantly less than one second. Since the horizontal gauge bosons could also induce FCNC processes in the SM sector, bounds can be derived on the related effective $SU(2)_H$ Fermi constant $G^H_{\mu} = \sqrt{2}g_H^2 \ 8M^2_H$. Naturally, such bounds are stronger if the two SM generations involved contain the lightest fermions of each type (e.g., $e$ and $\mu$ rather than $\mu$ and $\tau$), since these FCNC have stronger experimental constraints. In Fig. 1 we show contours for the lower bound on $G^H_{\mu}$ such that the lifetime of the dark mesons is smaller than $10^{-2}$ s as a function of the dark meson mass $m_H$ and decay constant $f_H$. Notice that the values of these two quantities will depend on the strength of the $SU(3)_{DC}$ interaction as well as the masses of the dark matter fermions. In any case the “dark meson” masses should be heavier than $\sim 100$ MeV so that they decay before BBN but lighter than the “dark baryon” mass so that the symmetric component is stored mainly in mesons and not baryons and antibaryons, this corresponds to the maximum value of $m_H$ depicted in Fig. 1. If the dominant decay channel is to a muon pair (left panel), then the bound is typically of $O(10^{-10})$ GeV$^{-2}$, while the bounds are about an order of magnitude weaker for decays into a tau and a lighter lepton (right panel). In this last case the decay can only happen if $m_H > m_{\tau}$, which corresponds to the horizontal asymptote.

On the other hand, the strongest constraint on $G^H_{\mu}$ from FCNC stems from the bound on the decay $K \to \epsilon \mu$ and implies that $G^H_{\mu} < 3.6 \cdot 10^{-12}$ GeV$^{-2}$, which would cause tension with the lower bounds derived in Fig. 1. However, this constraint does not apply if the horizontal symmetry is broken in stages. For example, this may be achieved by first breaking the $SU(2)_H$ to $U(1)_H$ by a real scalar triplet acquiring a vacuum expectation value along the $\sigma_3$ direction and giving large masses to the flavor changing gauge bosons while leaving the flavor conserving one massless. This procedure is similar to Georgi and Glashow’s model of electroweak interactions, which did not include neutral currents. The remaining flavor diagonal $U(1)_H$ can be subsequently broken at a scale low enough to obtain interactions of the strength required for
the dark mesons to decay into two muons. In this case the dominant decay channel of the dark mesons could be to two muons and the constraints on the left-handed panel of Fig. 1 would apply. Reconciling this scenario with the lower bound on $g_H$ from Eq. (4) is easy since the scale of the $SU(2)_H$ symmetry breaking is unrelated to the mass of the flavour-conserving $Z'$, for instance with $g_H = 0.5$ the sphalerons would reach thermal equilibrium at $T \lesssim 10^{11}$ GeV and the first stage of symmetry breaking, which would freeze out the sphalerons, should occur above $\Lambda \gtrsim 10^5$ GeV. In this scenario, which would be mainly flavour conserving at low energies, sizable interactions between the visible and dark sectors via a relatively light $Z'$ are allowed. Thus, a positive signal could be induced in direct DM detection searches and the extra $Z'$ boson can be searched for at the LHC. In principle the interaction between DM and the visible sector can be large enough so as to accommodate the DAMA and CoGeNT, that require $G_H^f < 10^{-7}$ GeV$^{-2}$.

The results from LEP-II suggest that, if the $Z'$ at low energies couples with full strength to electrons and other charged leptons then $G_H^f < 5 \times 10^{-9}$ GeV$^{-2}$, therefore, the coupling to electrons via the $SU(2)_H$ has to be subleading in order to evade this tension.

An interesting alternative would be to couple the two heaviest SM fermion generations to the $SU(2)_H$ and having the scalar triplet acquire its vev along the $\sigma_1$ direction. In this case the residual $U(1)_H$ would still induce FCNC in the $t - c$, $b - s$ and $\tau - \mu$ sectors but the constraints are in this case weaker and allow for sufficiently fast dark meson decays. Indeed, such a $U(1)_H$ with strength $G_H^f = 7 \times 10^{-11}$ GeV$^{-2}$ is allowed by present data and would contribute to CP violation in the $B_s$ system, accommodating the observed dimuon anomaly at Tevatron. In this case the dark mesons would decay into a tau and a muon and the constraints depicted in the right panel of Fig. 1 would apply. In this scenario, it is also possible to identify the scale of the $SU(2)_H$ symmetry breaking with the mass of the flavour-changing $Z'$ contributing to $B_s$ mixing. In combination with Eq. (4) this would imply that $g_H \gtrsim 0.06$ and $\Lambda \gtrsim 2.7$ TeV, for the dark sphalerons to enter in thermal equilibrium at $T \gtrsim \Lambda$. In this case, direct detection experiments and production at colliders would be much more challenging, given the suppressed interaction between the dark and visible sectors. On the other hand, observable new contributions to FCNC in $B$ physics would be expected.
References

18. M. Gell-Mann, P. Ramond and R. Slansky,