Relating leptogenesis and dark matter

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A scenario that relates the abundance of dark matter to the baryon asymmetry of the Universe is presented. In this scenario, based on a left-right extension of the Standard Model, dark matter is made of light, $M \sim 1\text{ GeV}$, for all practical matters non-interacting, right-handed Majorana neutrinos.

1 Introduction

Only one fifth of matter in the universe is made of atoms, according to the so-called ”concordance model” of cosmology. These atoms, or baryons, are thought to have survived to annihilation with the anti-matter that filled the early universe thanks to the existence of a primordial baryon asymmetry. This baryon asymmetry, in turn, could have been generated dynamically, typically in the very early universe, following a scheme known as baryogenesis.

The rest of matter in the universe is supposedly made of Dark Matter, a speculative component proposed already many decades ago in order to explain the dispersion of velocities of galaxies bound in clusters. The simplest model of dark matter posits the existence of a thermal relic of stable, weakly interacting massive particles or WIMPs. Those were in thermal equilibrium in the early universe, but then fell out of equilibrium, leaving an abundance that is simply related to their annihilation cross-section. Dark matter of that kind is already expected to exist. We believe that there is a cosmic background of Standard Model (SM) neutrinos, that decoupled around $T \sim 1\text{ MeV}$ when the weak interactions fell out of equilibrium, incidentally a first step toward the synthesis of the lightest elements. Those neutrinos are massive, but there are not heavy enough to be the dominant form of dark matter in the universe. Large-scale structures formation lore requires dark matter to consist of (or to be equivalent to) particles that are heavier than $\sim 100\text{ eV}$, while the neutrinos we know of have a mass of at most $\sim 1\text{ eV}$. Hence there must be something else. The most popular, well-motivated, and indeed quite successful
candidate for dark matter beyond the SM is a neutralino, the lightest, preferably neutral, of the
supersymmetric partners of the known particles.

This might be all correct. Yet, there is a generally overlooked puzzle posed by these somewhat
standard approaches to the matter problems of the universe. If baryons ought their survival to
baryogenesis and dark matter its existence to freeze-out, phenomena that, supposedly, took
place at very different times in the early universe, how come that their abundance are so similar
today? Notice that while the ratio
\[ \frac{\Omega_{dm}}{\Omega_b} \sim 5 \]  \hspace{1cm} (1)
is preserved by the expansion of the universe nowadays, this what not the case after freeze-out
but while the baryons were still relativistic
\[ \frac{\Omega_{dm}}{\Omega_b} \propto a \]  \hspace{1cm} (2)
where \( a \) is the scale factor. Albeit not the most dramatic, this is one of the many adjustments
or fine-tuning problems posed by our (understanding of our) universe.

It is possible that the explanation for (1) is anthropic in origin. It could also be mere
serendipity. For instance, leptogenesis, a possible mechanism for the origin of the baryon asym-
metry, requires neutrinos to be massive, a requisite for dark matter. Things could hardly be
simpler (a missed opportunity for our universe) but, yet again, the known neutrinos can not be
the dominant form of dark matter. In the present proceedings, we will report on a recent at-
tempt to relate the baryonic and dark components using (a)symmetry principles. Specifically,
we shall relate the baryon asymmetry to a corresponding asymmetry in the dark matter. This
idea is not quite knew but, as usual, the devil is in the details. We develop a scenario,
based on the more recent work of Kitano and Low, which, for lack of something better, one
could dub ”Matter Genesis”, since both baryonic and dark matters have to be generated.

2 Outline of the model

We distinguish a visible and a dark sector. The SM particles belong to the visible sector, but
we will also add other states. As usual, the lightest particle of the dark sector is protected
from decay by a discrete symmetry, analogous to R-parity. In our scenario, this dark matter
candidate is a right-handed neutrino that we call the \( \nu_R \).

In our model, based on the gauge group \( SU(2)_L \times SU(2)_R \times U(1)_{B-L} \), the \( \nu_R \) interact
through the exchange of heavy \( SU(2)_R \) gauge bosons. Now we would like the abundance of \( \nu_R \)
to be similar to that of baryons \( n_{\nu_R} \sim n_b \). This constraint implies that the the mass of the \( \nu_R \)
is \( O(\text{GeV}) \) to account for the dark matter energy density, a mass scale much smaller than that
required by thermal leptogenesis. Second, as the \( \nu_R \) are very weakly interacting, the abundance
of \( \nu_R \) can not be thermal since otherwise \( n_{\nu_R} \sim n_\gamma \). To circumvent these tensions, we introduce,
following Kitano and Low, a odd-parity ”messenger particle”, that we call the \( D \). In our model,
the \( D \) are colored, \( SU(2) \) singlets states, and they carry a \( B-L \) number. A net \( D \) particle
\( B-L \) asymmetry will be produced at some high scale, together with a corresponding \( B-L \)
asymmetry in the even-parity sector, through a standard thermal leptogenesis mechanism for
which we need extra heavy Majorana states.

A model which contains all these ingredients has been proposed by Davidson \( et \ al \) as an
alternative way of giving mass to the quarks and leptons. It is known in the literature as the
”universal see-saw model”. The gauge group is \( SU(2)_L \times SU(2)_R \times U(1)_{B-L} \). The left and
right-handed quarks \( Q_{L,R} \) and leptons \( L_{R,L} \) are respectively \( SU(2)_L \) and \( SU(2)_R \) doublets and,
in the simplest framework, there are two Brout-Englert-Higgs (BEH) doublets,
\[ \phi_L \sim (2,1,1) \]
\( \phi_R \sim (1, 2, 1). \)

To give mass to the quarks and leptons, one introduces a set of SU(2) singlet Weyl fermions and Majorana fermions \( N \):

\[
U \sim (1, 1, 4/3) \quad D \sim (1, 1, -2/3) \quad E \sim (1, 1, -2) \quad N \sim (1, 1, 0).
\]

Note the unusual \( B-L \) charge assignment of these fields. The BEH bosons, for instance, have a non-zero \( B-L \) charge, and the \( N \) are singlet states. They play the role of the heavy Majorana particles necessary for leptogenesis.

![Diagram](image)

**Figure 1: Steps of Matter Genesis**

The sequence of events is summarized in Figure 1. A \( D \) particle excess (dark blue) is produced through the out-of-equilibrium decay of the heavy \( N \) states, together with an opposite \( B-L \) charge in the even-parity, visible sector (in pink). When the universe’s temperature reaches \( T \sim M_D \), the \( D \) and anti-\( D \) annihilate each other very efficiently, since they are strongly interacting colored states, leaving only a tiny \( D \) asymmetry. Meanwhile, in the visible sector, \( B+L \) violating electroweak processes generate a net baryon asymmetry. Eventually, the relic \( D \) particles decay into the \( \nu_R \) plus visible sector particles. If \( D \)-decay were to take place before electroweak symmetry breaking, the \( B-L \) asymmetry that was sort of kept apart in the invisible sector would be released free and all \( B \) and \( L \) excess would be washed out. Hence, an extra constraint is that \( D \) decay after electroweak symmetry breaking. The \( D \) are thus a bit schizophrenic; they are strongly interacting, heavy \( M_D \sim \text{TeV} \) states and yet they must be quite narrow, for they can only decay quite later in the history of the universe, \( \Gamma_D/M_D \sim 10^{-3} \) (a bit like neutrons). The last constraint we must remember is that the \( \nu_R \) can not come in thermal equilibrium, otherwise their thermal abundance would overshadow that produced by the decay of the \( D \). The universal see-saw models contains many parameters and, not surprisingly, all our constraints can be accommodated by the universal see-saw model with a \( D \) particle of mass \( \sim \text{TeV} \). The details can be found in the original article.}

[1]
[2]
3 Conclusions

The model presented here is not particularly attractive phenomenologically speaking but it offers nevertheless some interesting features. The sort of dark matter we are considering is by construction very weakly interacting. Hence, unfortunately, it will escape to both direct and indirect detection is any foreseeable future. On the other hand there are specific signals that could be seen at the LHC, if the $\tilde{D}$ particles, which are basically new quark states, albeit $SU(2)$ singlet ones, are not too heavy.

The dark matter candidate is produced non-thermally through the decay of the $\tilde{D}$ particles. They are thus initially very relativistic. However they have some time to lose their momentum and their streaming length is of the order of 1 $M_{pc}$ in the most interesting part of parameters space. The $\nu_R$ are thus a form of warm rather than cold dark matter, a feature which could be of interest for structure formation.

The least satisfying, but inevitable, aspect of the present scenario is that we have to fix by hand the mass of the $\nu_R$ to be of the same order as the mass of the light baryons $\sim$ 1 GeV. There has been some attempts at circumventing this issue. We would like to mention two such scenarios. The first one assumes the existence of new, exotic hadronic states, the mass scale comes in naturally, the drawback being that we know too much about strong interactions so that there is little room for speculation... The other attempt invokes the possibility of varying particle masses. In this approach baryons and dark matter masses are function of particle number densities. The main drawback is that it is not easy to reconcile this approach with constraints on mass variation.

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References

1. M. Tegmark, A. Aguirre, M. Rees and F. Wilczek, Phys. Rev. D 73 (2006) 023505 [arXiv:astro-ph/0511774].
2. N. Cosme, L. Lopez Honorez and M. H. G. Tytgat, Phys. Rev. D 72 (2005) 043505 [arXiv:hep-ph/0506320].
3. S. M. Barr, R. S. Chivukula and E. Farhi, Phys. Lett. B 241, 387 (1990) ; S. M. Barr, Phys. Rev. D 44, 3062 (1991).
4. D. B. Kaplan, Phys. Rev. Lett. 68, 741 (1992).
5. V. A. Kuzmin, Phys. Part. Nucl. 29, 257 (1998) [Fiz. Elem. Chast. Atom. Yadra 29, 637 (1998 PANUE,61,1107-1116.1998)] [arXiv:hep-ph/9701269].
6. R. Kitano and I. Low, Phys. Rev. D 71, 023510 (2005) [arXiv:hep-ph/0411133].
7. A. Davidson and K. C. Wali, Phys. Rev. Lett. 59, 393 (1987); S. Rajpoot, Phys. Rev. D 36, 1479 (1987).
8. R. Kitano and I. Low, [arXiv:hep-ph/0503112].
9. G. R. Farrar and G. Zaharijas, Phys. Rev. Lett. 96 (2006) 041302 [arXiv:hep-ph/0510079].
10. R. Catena, M. Pietroni and L. Scarabello, Phys. Rev. D 70 (2004) 103526 [arXiv:astro-ph/0407646].