PROCEEDINGS OF SCIENCE

The universe could be symmetric: dark matter stability and matter-antimatter asymmetry from baryon number conservation

Mar Císcar-Monsalvatje,*[*] Alejandro Ibarra and Jérôme Vandecasteele

Technische Universität München,
James-Franck-Straße, 85748 Garching, Germany

E-mail: mar.ciscar@tum.de, ibarra@tum.de, jerome.vandecasteele@tum.de

There is great evidence that dark matter constitutes most of the matter content in our universe. We also have measured a cosmological asymmetry between matter and antimatter. The nature of dark matter remains elusive, as does the origin of the matter-antimatter asymmetry. Still, the similarity between their current abundances hints towards a common origin. Also, as we can only see the visible component of matter, we cannot state that the universe is overall asymmetric. In this work, we study the possibility that the dark matter carries baryon number and hides the counterpart of the measured asymmetry. We introduce a model with two dark sector particles, one scalar and one fermion, carrying baryon number and initially having equal but opposite asymmetries. Following the principle of baryon number conservation, the particles in the dark sector interact with each other, and the fermionic one interacts with the Standard Model through the Neutron Portal. The scalar particle freezes out and generates the dark matter relic density, as it is naturally stable. The fermionic particle or "dark neutron" disappears from the thermal bath and transfers its asymmetry to the quarks via scatterings and decays. This scenario is viable and consistent with cosmological observations and collider constraints. Different phenomenological considerations entirely bound the parameter space available for the Neutron Portal and could be probed in the future.

ArXiv ePrint: 2307.02592

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08_01.09.2023
University of Vienna

[*]Speaker

PoS(TAUP2023)007

1. Introduction

Even though the Standard Model (SM) of particle physics accurately describes many physical phenomena, some problems still need further explanation. Two of the most relevant open questions in cosmology are the origin of the matter-antimatter asymmetry and the nature of dark matter (DM).

The visible universe is fundamentally made of particles, and little amount of antiparticles are found. We have measurements of the quark-antiquark asymmetry today, the most precise coming from the Cosmic Microwave Background (CMB) [1]

$$Y_{\Delta q,0} \equiv \left.\frac{n_q - n_{\bar{q}}}{s}\right|_0 = (2.63 \pm 0.07) \times 10^{-10}. \quad (1)$$

However, the mechanism which generated this asymmetry in the early universe (baryogenesis) is still unknown. In 1967, Sakharov introduced the three necessary conditions to generate an asymmetry of baryons [2]: i) baryon number (B) violation, ii) C and CP violation, and iii) departure from thermal equilibrium. These conditions are still the standard guidelines for formulating baryogenesis mechanisms today. Additionally, we have firmly established the presence of dark matter by observing its gravitational effects across different scales. The energy density of the dark matter component today has also been measured from the CMB and is found to be similar to the Standard Model energy density: $\Omega_{\rm DM} \simeq 5\Omega_{\rm SM}$ [1]. Yet, the nature of the dark matter itself remains still unknown. As far as we know, dark matter particles could carry baryon number as ordinary matter.

In fact, we do not have evidence that the universe is overall baryon asymmetric, as we can only measure its visible component. The missing baryon number could be hidden in the dark sector, resulting in an overall zero baryon number. In this scenario, we do not need to fulfill the first of the Sakharov conditions, B-violation. We merely need C and CP violation, a departure from thermal equilibrium, and a portal between the dark sector and the quarks. Furthermore, analogously to the proton, dark matter would be naturally stable from just baryon number conservation.

In the following, we describe some realization of this idea, with the initial condition and dynamics in section 2 and the phenomenology and potential signals of the scenario in section 3.

2. A baryonic dark sector and its dynamics

We introduce two dark sector particles, a complex scalar, χ, which will play the role of dark matter, and a Dirac fermion, N. Both particles are charged under baryon number as $B(\chi) = -1$ and $B(N) = +1$. As an initial condition, both species have an equal particle-antiparticle asymmetry such that the net baryon number is zero. Some unspecified mechanism in the dark sector is assumed to produce an excess of N over $\overline{N}$ at high temperatures. This mechanism operates exclusively in the dark sector, and by conservation of baryon number, the generation of an excess of χ over χ^* is also produced, as depicted in Fig. 1. [1]

The B-conserving interaction terms among the particles in the dark sector are

$$\mathcal{L} \supset \frac{1}{\Lambda_0}\chi\chi^*\overline{N}N + \frac{1}{\Lambda_2}\left(\chi\chi\overline{N^c}N + h.c.\right), \quad (2)$$

[1]A possible mechanism generating this excess could be the out-of-equilibrium, CP-violating, and B-conserving decays of heavy fermions $\varphi_i \to \chi N, \chi^*\overline{N}$, which will generate an asymmetry between the number densities of N and $\overline{N}$, and the corresponding asymmetry between χ and χ^*, rendering a total baryon number equal to zero.

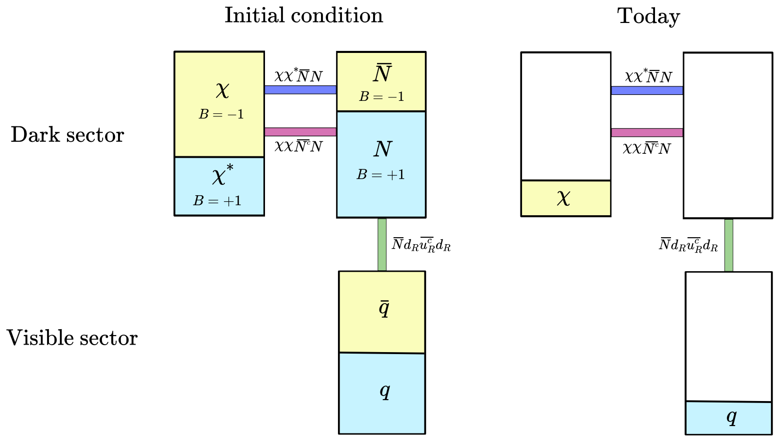

Figure 1: Sketch of the initial (left) and final (right) abundances of the different particle species in our model, together with the interaction terms among them. Light yellow (blue) indicates the particles with $B < 0$ ($B > 0$); the total B of the universe is equal to zero. Here, we have assumed that the dark matter efficiently annihilated such that it is totally antisymmetric today, but it is also possible to have a small component of antiparticles. For the generalized picture where the initial condition happens before Sphaleron freeze-out, see Figs. 1 and 3 in the main paper [3].

with Λ_0 and Λ_2 the corresponding energy scales. The first term in Eq. (2) mediates interactions that drive dark matter freeze-out, so Λ_0 must be sufficiently low for these interactions to be efficient. As χ freezes out, only the asymmetric component is left[2], generating the relic abundance. Because χ is the lightest spin-0 particle carrying baryon number, it is naturally stable and constitutes the dark matter.

In order to transfer the asymmetry to the visible sector, we introduce the B-conserving Neutron Portal [4] of the form

$$\mathcal{L} \supset \frac{1}{\Lambda_n{}^2}\left(\bar{N}\, d_R\, \overline{u_R^c} d_R + h.c\right), \tag{3}$$

with H the Standard Model Higgs doublet and u_R and d_R the right-handed up and down quarks. Due to this interaction, the scatterings $N\bar{d} \leftrightarrow ud$ and $N\bar{u} \leftrightarrow dd$ and later the decays $N \rightarrow udd$ inject a net baryon number into the visible sector. Through these decays, the fermion N disappears from the thermal bath, leading to the complete transfer of its asymmetry to the Standard Model quarks.

The second term in Eq. (2) is associated with washout processes and tends to erase the asymmetry within each dark sector particle species. The scale Λ_2 must be large enough to not erase the asymmetry completely, which would result in no asymmetry to transfer to the visible matter.

Finally, quarks and antiquarks annihilate in pairs, leaving only the asymmetric component we see today. An equal but opposite asymmetry remains in the visible and dark sector, as shown in the right part of Fig. 1. The dark matter stability is then strongly linked to the quark-antiquark asymmetry. This picture is slightly different when the initial asymmetry in the dark sector is

[2]It is also possible to have larger values of Λ_0 such that not all the symmetric component is annihilated, which will lead to smaller dark matter masses.

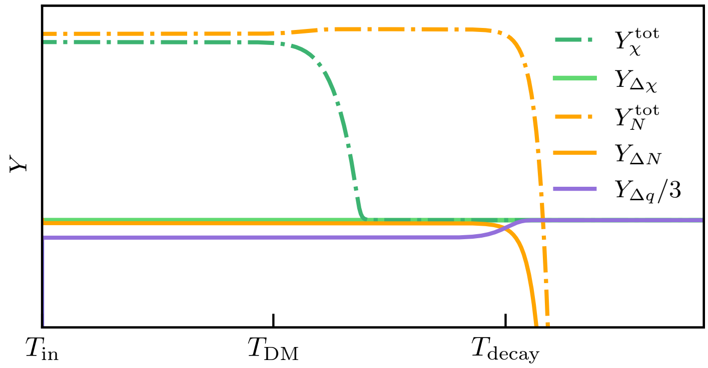

Figure 2: Representative evolution of the total yields of $\chi + \chi^*$ and $N + \bar{N}$ (dash-dotted) and the yields of the different asymmetries between particles and antiparticles (solid). The evolution of the asymmetries fullfills at all times the condition $B(\chi)Y_{\Delta\chi} + B(N)Y_{\Delta N} + B(q)Y_{\Delta q} = 0$. For the generalized picture where the initial condition happens before Sphaleron freeze-out, see Fig. 2 in the main paper [3].

generated before the electroweak sphaleron freeze-out. In this case, the number $B - L$ is always conserved, and part of the asymmetry of the quarks is reprocessed into the leptons. In the end, the dark matter asymmetry is compensated by the quark-lepton asymmetry, and the universe is $B - L$ symmetric. You can find more details about the implications of this in the main paper [3].

This scenario predicts a highest possible dark matter mass of 5 GeV (3.4 GeV if sphalerons are active when the asymmetry is generated) when dark matter is effectively depleted before freeze-out, but lower masses are also reachable.

In Fig. 2, one can see the evolution of the abundance of each particle species, along with its asymmetries. Initially, an equal asymmetry is generated for χ and N, and by scattering mediated by the Neutron Portal, the asymmetry in N is very quickly partially redistributed to the quarks. Around $T_{\rm DM} \sim m_{\rm DM}$, χ particles freeze out, setting the relic abundance. At later times, when N decays away, its remaining asymmetry is transferred to the quarks and matches the dark matter asymmetry.

3. Constraints and the Neutron Portal

We do not expect signals from direct or indirect detection due to the high suppression of the involved processes[3]. However, we have detection prospects with interesting signals for probing the Neutron Portal. Via this portal, N can impact the cosmological history, could be explored in colliders, and has a well-defined viability window, as illustrated in Fig. 3.

The abundance of N at the time of dark matter freeze-out is large, so if they are sufficiently long-lived, they could dominate the energy content of the early universe once they become non-relativistic [5]. This would impact the cosmological history as it would lead to a phase of early matter domination (purple line in Fig. 3). To preserve the standard Big Bang Nucleosynthesis picture, we will require that the yield of N is largely depleted at ~ 1 s, giving rise to the excluded orange area in Fig. 3.

[3]As χ is a scalar, it could also be probed through a Higgs portal interaction. However, this interaction plays no role in the described dynamics.

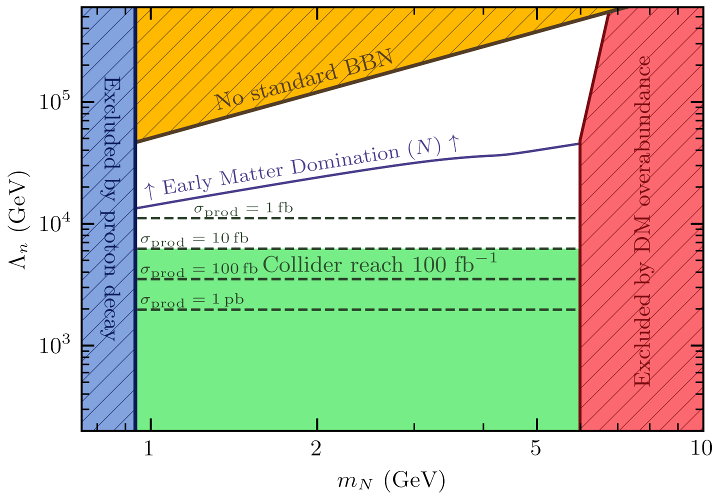

Figure 3: Constraints on the Neutron Portal energy scale (Λ_n) and mass of N (m_N) from cosmology (orange), proton stability (blue), dark matter overabundance (red), and collider experiments (green), along with contours of production cross section and decay length at the LHC with $\sqrt{s} = 14$ TeV. The allowed region is shown in white. Plot taken from the main paper [3].

Through the Neutron Portal, N is also produced in proton-proton collisions through the partonic processes $ud \to N\bar{d}$ and $dd \to N\bar{u}$. N is expected to be a highly boosted long-lived particle on the scale of the LHC detectors and could be detected via the imbalance in the transverse energy of collision events. We indicate in the plot the values of Λ_n corresponding to a production cross section $\sigma_{pp\to N+\text{jet}} = 1$ fb, 10 fb, 100 fb, and 1 pb, and in green the ballpark area of values that can be probed at the LHC with an integrated luminosity of $\mathcal{L} = 100$ fb^{-1}.

The mass of N is bounded from below by the requirement that the proton must be the lightest fermion carrying baryon number, which results in the blue excluded area. Lastly, the mass of N is bounded from above by the requirement that the dark matter is not overproduced. More specifically, the annihilation process $\chi\chi^* \to N\overline{N}$ must be efficient enough to deplete most of the dark matter density, which gives us an upper bound for the mass of N as shown in the solid red shaded area [6]. In the case where the initial asymmetry is generated while sphalerons are still active, this limit becomes more stringent as the dark matter mass is lower.

The allowed region is shown in white, with well-defined boundaries determined by a range of different phenomenological considerations. This window could be entirely probed in future colliders.

4. Conclusions

We have presented a scenario that accommodates dark matter and a quark-antiquark asymmetry. We postulate the existence of a scalar and a fermionic particle in the dark sector, both carrying baryon number. As initial conditions, we have assumed that at very high temperatures, the universe has zero baryon number, but the dark sector species contain an asymmetry between particles and antiparticles. We have argued that the asymmetry in the fermionic particle can be transmitted to the visible sector through (baryon conserving) Neutron Portal interactions, thus resulting in a quark-antiquark asymmetry (and possibly a lepton-antilepton asymmetry via sphalerons). On the other hand, the scalar particle is stable due to the baryon number conservation and constitutes the dark matter candidate.

In this framework, the baryon number of the visible sector is exactly compensated by an opposite asymmetry in the dark sector, thus linking the observed quark-antiquark asymmetry to the existence of dark matter. Under reasonable assumptions, we expect the dark matter mass to be $m_{\rm DM} \sim 5$ GeV when it is fully asymmetric or potentially lighter if a population of dark matter antiparticles remains after freeze-out.

Such a particle could be produced at the LHC or in flavor physics experiments through the Neutron Portal, generically leaving the detector before decaying. This particle would produce a missing energy signal and an apparent baryon number violation. The parameter space for probing the Neutron Portal is completely bounded and could be potentially entirely probed.

Acknowledgments

This work is supported by the Collaborative Research Center SFB1258 and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC-2094 - 390783311. MCM would like to thank the organizers of the TAUP 2023 conference for the opportunity to present her work.

References

[1] Planck collaboration, *Planck 2018 results. VI. Cosmological parameters*, Astron. Astrophys. **641** (2020) A6 [1807.06209].

[2] A.D. Sakharov, *Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe*, Pisma Zh. Eksp. Teor. Fiz. **5** (1967) 32.

[3] M. Císcar-Monsalvatje, A. Ibarra and J. Vandecasteele, *Matter-antimatter asymmetry and dark matter stability from baryon number conservation*, 2307.02592.

[4] B. Fornal and B. Grinstein, *Dark Matter Interpretation of the Neutron Decay Anomaly*, Phys. Rev. Lett. **120** (2018) 191801 [1801.01124].

[5] R. Allahverdi and J.K. Osiński, *Early matter domination from long-lived particles in the visible sector*, Phys. Rev. D **105** (2022) 023502 [2108.13136].

[6] K. Griest and D. Seckel, *Three exceptions in the calculation of relic abundances*, Phys. Rev. D **43** (1991) 3191.