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Asymmetric dark matter in early Universe chemical equilibrium always leads to an antineutrino signal

Hajime Fukuda, Shigeki Matsumoto, and Satyanarayan Mukhopadhyay
Kavli IPMU (WPI), The University of Tokyo, Kashiwa, Chiba 277-8583, Japan
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Under rather generic assumptions, we show that, in asymmetric dark matter (ADM) scenarios in which the ADM sector was in chemical equilibrium with the standard model sector in early epochs, the sign of the B − L asymmetry stored in the dark matter sector and the standard model sector are always the same. One particularly striking consequence of this result is that, when such an ADM decays or annihilates in the present universe, the resulting final state always involves an antineutrino. As a concrete example, we construct a composite ADM model and explore the feasibility of detecting such an antineutrino signal in atmospheric neutrino detectors.

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I. INTRODUCTION

The experimental probes of particle dark matter at present are primarily motivated by the most widely studied paradigm of weakly interacting massive particles (WIMPs). The appeal of the WIMP hypothesis lies in the fact that a particle with mass typically in the range of 100 to 1000 GeV correctly leads to the observed dark matter (DM) density—a fact that is largely independent of the details of the model under consideration, assuming a standard thermal history of the universe [1]. Intriguing alternatives, however, do exist in the DM model space, which lead to equally generic predictions as in the WIMP scenarios. Asymmetric dark matter (ADM) is one such class of models that has been widely studied [2]. Though an ADM scenario can be realized via different mechanisms, in this paper, we focus on the class of models where the DM and the standard model (SM) sectors were in chemical equilibrium in the early Universe, with the net B − L asymmetry of the universe shared between the two sectors. In such a case, an ADM with a mass in the range of 1 to 10 GeV leads to the observed ratio of baryon to DM densities, which is again largely independent of the model details in a standard thermal history of the Universe. For our subsequent discussion, we refer to this class of ADM models in which chemical equilibrium with the SM particles is invoked. For alternative realizations of the ADM idea without requiring such chemical equilibrium, and their phenomenological implications, we refer the reader to Refs. [2–4]. We also note that in the latter class of ADM scenarios the universe always remains symmetric in some linear combination of the dark and visible baryon numbers, while in the class of models we focus on, a net asymmetry is generated in the B − L quantum number.

With the above alternative solution to the DM puzzle in mind, it is important to look for experimental signatures that can discriminate an ADM from a WIMP. To maintain thermal equilibrium in the early Universe, WIMPs must interact with the SM particles. In most cases, this leads to unsuppressed WIMP annihilations to SM final states in the present universe as well, which are being looked for in various indirect detection experiments [5]. Usually, for a WIMP particle that is identical to its antiparticle, the annihilation final states include an equal number of SM particles and antiparticles of a given variety. Although ADMs also interact with the SM sector to be in chemical equilibrium in the early Universe, there is a crucial difference in the expected decay or annihilation products in the present universe. The ADM particles are charged under the $U(1)_{\mathrm{B-L}}$ symmetry, which is conserved in all interactions. This leads to a final state with a nonzero B − L charge, with different numbers of SM particles and antiparticles of a given species—a fact that can be utilized to distinguish an ADM from a WIMP [6].

This has interesting consequences in the signatures of the ADM particle. For example, the same interaction leading to the chemical equilibrium can cause decay or annihilation of the ADM particles in the present universe. In such a case, we find that it would always produce final states with a positive B − L charge [the convention followed by us fixes the baryon number of the universe observed today (in visible matter) to be positive]. This fact implies that the resulting final states always involve an antineutrino. This is because, in the SM, neutrinos are the only stable particles carrying a nonzero B − L charge and are electrically neutral. On the other hand, other stable particles carrying a B − L charge, namely, the electron and the proton, are electrically charged and must be produced in pairs to make the final state electrically neutral. Such pairs, however, do not carry a net B − L charge. This fact leads to a rather striking signal in large volume atmospheric neutrino detectors that can separate neutrinos from antineutrinos to a good accuracy: an antineutrino signal with an energy of 1 to 10 GeV. We emphasize here that, although the prediction for *either* only a neutrino *or* only an antineutrino

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signal depending upon the B − L charge of the surviving ADM particle was made in past studies, our results show that chemical equilibrium determines the surviving ADM (anti)particle to always have a positive B − L charge, independent of the interaction term involved.

In what follows, we first prove that the sign of the B − L asymmetry stored in the dark matter sector and the SM sector are always the same under rather generic assumptions on the ADM scenario. Thereafter, as a concrete example, we construct an explicit model of composite ADM, which is a hidden baryon of a confining $SU(3)_{\rm D}$ gauge symmetry. Finally, we discuss its decay signatures in the form of antineutrinos and their detectability in ongoing and near-future experiments.

II. B − L ASYMMETRY STORED IN DM SECTOR

In the ADM scenarios under consideration, a B − L asymmetry is postulated to be generated by a baryogenesis mechanism in the early Universe, leptogenesis [7] being one of the promising ways, which at the same time enables us to explain tiny neutrino masses via the seesaw mechanism [8]. Since the ADM particle is charged under B − L, the net B − L asymmetry will get distributed between the DM and the SM sectors if there exists an interaction maintaining chemical equilibrium between them. The interaction has to be active after baryogenesis and conserve B − L (but violate the DM number) in order not to wash out the generated asymmetry. The relative magnitudes of the asymmetry stored in each sector can be computed using the conditions of detailed balance [9]. In fact, using a general method described in Ref. [10], we can obtain these relative magnitudes without referring to the details of a specific set of reactions, once the conserved quantum numbers of all the particles in equilibrium are known.

We start with a set of particle species i in the reactions, each having a set of conserved quantum numbers q_{ia}, where the index a runs over all the conserved quantum numbers for, e.g., B − L, hypercharge Y, the third component of the weak isospin T_3, etc. When the interactions between all the particles are sufficiently weak, the chemical potentials of species i (denoted by μ_i) can be expressed as linear combinations of the chemical potentials of the conserved charges (denoted by ξ_a):

$$\mu_i = \sum_a q_{ia}\xi_a. \tag{1}$$

In the temperature (T) of our interest, all the particles can be considered as highly relativistic. When the chemical potential μ_i is sufficiently smaller than T, the difference between the particle and antiparticle number densities of species i is given by $n_i - \bar{n}_i = \tilde{g}_i\mu_i T^2/6$, with $\tilde{g}_i$ being the spin degrees of freedom, but with an additional factor of 2 for bosons. With the asymmetries of the conserved charges $A_a \equiv \sum_i q_{ia}(n_i - \bar{n}_i)$, the difference is eventually expressed by the asymmetries,

$$n_i - \bar{n}_i = \sum_{a,b}\tilde{g}_i q_{ia} M^{-1}_{ab} A_b, \qquad M_{ab} \equiv \sum_i \tilde{g}_i q_{ia} q_{ib}, \tag{2}$$

where a and b run over all the conserved charges, while i runs over all the particles in chemical equilibrium. It is worth noting that the matrix M has a positive definite determinant and hence is invertible.

We are now in a position to apply Eq. (2) to the ADM scenario with the following three assumptions:

(i) In the DM sector, there is no particle charged under the SM gauge group.
(ii) The DM sector chemically decouples from the SM one at the temperature $T_{\rm dec}$ in the early Universe.
(iii) Then, the B − L asymmetry stored in the DM (SM) sector gives the DM (baryon) density today.

First of all, since the only asymmetry with a nonzero value in the early Universe is that of the B − L charge, the above equation is simplified as

$$n_i - \bar{n}_i = \sum_a \tilde{g}_i q_{ia} M^{-1}_{a1} A_1, \tag{3}$$

where the index 1 denotes B − L. The next step is to determine how the net B − L asymmetry of the universe is distributed between the DM and the SM sectors. Since it can be shown that it is sufficient to consider the 2 × 2 block of the matrix M in the B − L and hypercharge Y basis, the asymmetry stored in the SM sector is

$$A_{\rm SM} = \sum_{i\in {\rm SM}} \tilde{g}_i [q_{i1}q_{i1}M^{-1}_{11} + q_{i1}q_{i2}M^{-1}_{21}]A_1, \tag{4}$$

where $A_{\rm SM} \equiv \sum_{i\in{\rm SM}} q_{i1}(n_i - \bar{n}_i)$ and the index 2 denotes the hypercharge Y. For convenience, let us define a matrix N_{ab}, which is similar to M_{ab}, with the sum going over only the particles in the SM sector:

$$N_{ab} \equiv \sum_{i\in{\rm SM}} \tilde{g}_i q_{ia} q_{ib}. \tag{5}$$

Since none of the particles in the DM sector carries a nonzero hypercharge, i.e., $q_{i2} = 0$ when $i \in {\rm DM}$, we have $M_{12} = N_{12}$ and $M_{22} = N_{22}$. In addition, we also have the inequality $M_{11} > N_{11} > 0$, which leads to $\det{\rm M} > \det{\rm N}$. Using this in Eq. (4), it very simply follows that

$$\frac{A_{\rm DM}}{A_{\rm SM}} = \frac{\det{\rm M} - \det{\rm N}}{\det{\rm N}} > 0, \tag{6}$$

where $A_{\rm DM} \equiv \sum_{i\in{\rm DM}} q_{i1}(n_i - \bar{n}_i) = A_1 - A_{\rm SM}$ is the B − L asymmetry stored in the DM sector. Thus, it is very generally true that the B − L asymmetries stored in the DM and the SM sectors have the same sign.[1]

[1]Our result is a general extension of that in Ref. [11] and is not altered even if other new conserved charges exist as long as B − L is the only one shared by both the DM and the SM sectors.

This fact implies that the ADM particles that survived up to the current epoch always have a positive B − L charge. As a result, when it decays or annihilates into SM particles in the present universe, the resulting final state always involves, at least, an antineutrino, as mentioned earlier. The only exception is the decay into a stable atom like deuterium, the branching fraction of which is, however, usually subdominant [12]. In ADM scenarios in which chemical equilibrium is not realized, the B − L charge stored in the DM sector is model dependent and can either be positive (in mirror DM models [3]) or negative (in hylogenesis [4]).

III. COMPOSITE ADM MODEL

The operator responsible for the chemical equilibrium between the DM and the SM sectors is obtained by integrating out all other fields of the DM sector, except the ADM fields. The particular form of the interaction depends on the model details; however, it can always be written as a higher-dimensional operator suppressed by some high scale, Λ_{ADM}.

As an attractive possibility, we consider a composite ADM model, in which the DM sector is described by an unbroken strongly coupled $\mathrm{SU}(3)_{\mathrm{D}}$ gauge theory with N_f vectorlike ‘dark’ quarks in the fundamental representation. The ADM particle is then a dark baryon composed of three dark quarks. A composite model allows us to consider the decay of the ADM particle without introducing a very small coupling constant. Furthermore, it predicts a large annihilation cross section of the dark matter and anti-dark matter particles into dark mesons. Such a large annihilation cross section is mandatory in the ADM scenario to eliminate the symmetric component of the DM density from the universe.

The lowest-dimension interaction between the two sectors conserving B − L and violating the DM number is

$$\mathcal{L}_{\mathrm{ADM}} = \frac{1}{\Lambda_{\mathrm{ADM}}^3}(\bar{\psi}_i^c \psi_j)(\bar{\psi}_k^c L)H + \mathrm{H.c.}, \tag{7}$$

where ψ_i denotes the quarks in the dark sector, with i being their flavor index, while L and H denote the SM lepton and Higgs doublets, respectively. The $\mathrm{SU}(3)_{\mathrm{D}}$ and $\mathrm{SU}(2)_{\mathrm{L}}$ indices are contracted by the respective epsilon tensors, which are suppressed for brevity. We need at least two flavors in the dark sector, i.e., $N_f \geq 2$, since otherwise the operator vanishes identically.

This interaction plays the dominant role in maintaining the chemical equilibrium between the DM and the SM sectors and hence can be used to compute the mass of the ADM particle with the help of Eq. (6). Conservation of B − L then requires the charge of the ADM constituent quarks to be $q_{\psi,\mathrm{B-L}} = 1/3$ ($q_{\bar{\psi},\mathrm{B-L}} = -1/3$), and we obtain $\mathrm{detM} = 79 + 22N_f/3$ and $\mathrm{detN} = 79$. Here, we assume that there is no new particle charged under the SM gauge group. The ratio of the B − L asymmetries between the DM and the SM sectors is then computed as $A_{\mathrm{DM}}/A_{\mathrm{SM}} = 22N_f/237$. Remembering the fact that the ratio between A_{SM} and the baryon asymmetry observed today in visible matter (denoted by A_{B}) is given by $A_{\mathrm{SM}}/A_{\mathrm{B}} = 97/30$ [9] and A_{DM} gives the dark matter density today, the mass of the ADM particle is

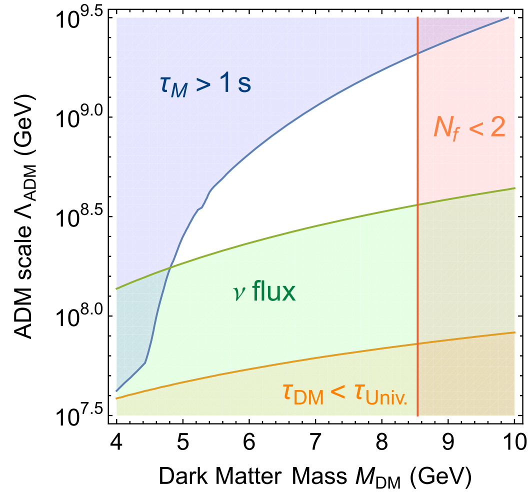

FIG. 1 (color online). Current constraints on the composite ADM model in the $(m_{\mathrm{DM}}, \Lambda_{\mathrm{ADM}})$-plane. See the text for details.

$$m_{\mathrm{DM}} = \frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{b}}}\frac{3555}{1067N_f}m_{\mathrm{N}} \simeq \frac{17}{N_f}\ \mathrm{GeV}, \tag{8}$$

where $m_{\mathrm{N}} \simeq 940$ MeV, $\Omega_{\mathrm{DM}} \simeq 0.12/h^2$, and $\Omega_{\mathrm{b}} \simeq 0.022/h^2$ are the nucleon mass, the dark matter, and the baryon abundances, respectively, with $h \simeq 0.67$ being the normalized Hubble constant. The condition $N_f \geq 2$ leads to an upper limit on the mass of the ADM particle, $m_{\mathrm{DM}} \leq 8.5$ GeV, as shown in Fig. 1.

To avoid a large amount of dark radiation in our universe, we introduce mass terms for the hidden quarks m_ψ. Assuming that two of the N_f flavors are sufficiently light, the light dark mesons [Nambu-Goldstone (NG) bosons denoted by M_i, $i = 1, 2, 3$] have the mass of $m_M^2 \simeq 2m_\psi \Lambda_c^3/f_M^2$, where Λ_c and f_M are the scale of the chiral condensate $-\langle\bar{\psi}\psi\rangle^{1/3}$ and the meson decay constant of $SU(3)_{\mathrm{D}}$, respectively. The mesons can decay into SM particles by mixing with the SM Higgs boson after EW symmetry breaking through the interaction

$$\mathcal{L}_M = \frac{1}{\Lambda_{\mathrm{ADM}}}\bar{\psi}_i i\gamma_5 \psi_j H^\dagger H. \tag{9}$$

Using the soft NG boson theorem, the mixing angle between the SM Higgs boson and a light meson M is estimated to be $\sin\theta \simeq 2v\Lambda_c^3/(f_M \Lambda_{\mathrm{ADM}} m_h^2)$ with $v \simeq 246$ GeV and $m_h \simeq 125$ GeV being the vacuum expectation value (VEV) and the mass of the Higgs boson, respectively. Needless to say, this is a very small mixing when $\Lambda_{\rm ADM}$ is much larger than the EW scale, and hence the properties of the SM Higgs boson are not modified by any appreciable amount. Such a mixing also leads to spin-independent DM-nucleon scatterings, which, however give a rather weak bound of $\Lambda_{\rm ADM} \gtrsim \mathcal{O}(10^6\ \mathrm{GeV})$ using the current LUX limits for $m_{\rm DM} \sim \mathcal{O}(10\ \mathrm{GeV})$ [13].

The light meson can, however, undergo a late time decay, and in order not to disturb the successful big bang nucleosynthesis, its lifetime should be shorter than about 1 sec. In terms of the mixing angle $\sin\theta$, the lifetime is $\tau_M = (\sin\theta)^{-2}/\Gamma_h(m_M)$, where $\Gamma_h(m_M)$ is the total decay width of a SM-like Higgs boson with a mass of m_M [14]. Since τ_M becomes shorter when m_M is larger, we fix the hidden quark mass to be $m_\psi = f_M$ as the most conservative choice, which is the maximum possible value if the hidden quark mass term is to be treated perturbatively. Imposing the constraint $\tau_M \lesssim 1$ sec leads to an upper limit on $\Lambda_{\rm ADM}$, as shown in Fig. 1. Here, we adopt simple scaling laws, $\Lambda_{\rm QCD}/m_N = \Lambda_c/m_{\rm DM}$ and $f_\pi/m_N = f_M/m_{\rm DM}$, to estimate Λ_c and f_M with $\Lambda_{\rm QCD} \simeq 242$ MeV and $f_\pi \simeq 92$ MeV being the chiral condensate of QCD and the pion decay constant. This limit is weakened if we introduce a new physics scale $\Lambda_M < \Lambda_{\rm ADM}$ assuming this new physics does not break the DM number. This would lead to a larger $\sin\theta$ and a detectable signal in direct detection experiments [15].

The interaction in Eq. (7) induces the decay of the ADM particle. After the Higgs field acquires a VEV, it gives rise to a four-Fermi interaction between three dark quarks and one neutrino, suppressed by $\sqrt{2}\Lambda_{\rm ADM}^3/v$. Adopting the analogous calculation of proton decay in grand unified theories, we estimate the width of the dominant decay mode, DM $\to \bar{\nu} + M$ as

$$\Gamma_{\rm DM} \simeq \frac{3v^2 m_{\rm DM}}{64\pi\Lambda_{\rm ADM}^6}|W_0(0)|^2\left(1-\frac{m_M^2}{m_{\rm DM}^2}\right)^2, \qquad (10)$$

where the form factor $W_0(0)$ is obtained from the hadron matrix element, $\langle M|(\bar{\psi}_i^c\psi_j)\psi_k|DM\rangle$, which is evaluated to be $\sim 0.1\ \mathrm{GeV}^2(m_{\rm DM}/m_N)^2$ by a simple scaling of the lattice results [16]. It then turns out that the lifetime of the ADM particle, $\tau_{\rm DM} \equiv 1/\Gamma_{\rm DM}$, is longer than the age of the universe when $\Lambda_{\rm ADM} \gtrsim 10^{7.5-8}$ GeV.

As expected from the theorem proved in the previous section, the decay of the ADM particle always produces an antineutrino, which gives a monochromatic signal with an energy of $E_{\bar{\nu}} \simeq (m_{\rm DM}^2 - m_{\rm M}^2)/(2m_{\rm DM})$. There are existing bounds on an excess in neutrino flux over the predicted atmospheric flux from the measurements by the Super-Kamiokande (SK) collaboration. We follow the analysis developed in Ref. [17], where the SK data on upgoing muon neutrino events from the whole sky collected during April 1996 and July 2001 were used to obtain an upper bound on the excess flux. This translates to a lower limit on $\Lambda_{\rm ADM}$, which is shown in Fig. 1.

All the current limits on the composite ADM model are summarized in Fig. 1. As we can see, the mass of the ADM particle is constrained from both above and below, 5 GeV $\lesssim m_{\rm DM} \lesssim 8.5$ GeV, and it implies that the number of flavors in the DM sector, N_f, can be either two or three. It is also worth emphasizing that, since the scale of leptogenesis, and hence of B − L generation, is expected to be $\mathcal{O}(10^{10})$ GeV, there exists an order of magnitude window in $\Lambda_{\rm ADM}$ to distribute the B − L asymmetry between the SM and the dark sectors.

The ultimate test of such a scenario would of course be to establish an antineutrino line signal, which would then require detectors that can separate neutrinos from antineutrinos to a good accuracy. In the absence of a magnetized detector with a sufficiently large volume, this is difficult to achieve. A qualitative discussion on this subject can be found in Ref. [6], where the capabilities of some present and future detectors were reviewed. It turns out that among the present ones the MINOS detector, having a magnetic field, might be able to establish a signal if the statistics is sufficient, while in the future Hyper Kamiokande, DUSEL, or INO holds the promise to distinguish a low-energy antineutrino signal.

IV. SUMMARY

Under the assumption of chemical equilibrium between the DM and SM sectors at some early epoch, we have proved the general result that the relative sign of the B − L asymmetries stored in the DM and SM sectors are the same, and it leads to a striking consequence in ADM phenomenology: an antineutrino is always produced when the ADM particle decays or annihilates. We have constructed a composite ADM model to demonstrate this idea and have shown that the decay of the ADM indeed produces a detectable antineutrino signal.

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