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Féeton ($B - L$ gauge boson) dark matter testable in future direct detection experiments

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Abstract: In this paper, we revisit the féeton (gauge boson of $\mathrm{U}(1)_{B-L}$ symmetry) dark matter scenario, and first point out the U(1) gauge symmetry can be a linear combination of the $B - L$ and the SM hypercharge gauge symmetries. With the redefinition of $B - L$ charge of fermions, the coupling between electron and féeton can be enhanced. After showing the parameter space required from the DM stability and cosmic production, we discuss the potential for verifying them in dark matter direct detection experiments. The results show that future experiments, such as SuperCDMS, have a sensitivity to reach the féeton DM region consistent with its cosmic production.

Keywords: Models for Dark Matter, New Gauge Interactions, New Light Particles

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Contents

1 Introduction

Many astrophysical observations suggest that 80% of the matter in the universe is dark matter (DM) [1–3]. However, we still do not know what DM is. A widely accepted conjecture is that DM consists of new particles beyond the framework of the standard model (SM) [1–3]. To be well-motivated, models of DM are typically concise extensions of the SM and capable of addressing certain issues within the SM simultaneously. For example, WIMPs predicted from supersymmetry [4, 5], axions proposed to address the Strong CP problem [6–8]. Yet, positive results for the detection of these mainstream candidates are still pending [9–12], leading to other possibilities regarding DM.

The U(1) $B-L$ gauge theory is an attractive theory beyond the standard model. This gauge theory requires three right-handed neutrinos (RHNs) to cancel the gauge anomalies and its spontaneous breaking induces the super heavy Majorana masses for these RHNs [13]. These heavy Majorana RHNs are a key point for generating the observed tiny masses for the active neutrinos (via the seesaw mechanism) [14–17] and for the creation of the baryon-number asymmetry in our Universe (by the leptogenesis) [18, 19]. Furthermore, the $B-L$ gauge boson is an inevitable prediction in this framework, and we have stressed recently that it can be a good candidate for DM [20] called as the féeton DM [21, 22]. In this paper, we revisit the physics and parameter space of the féeton dark matter. For the first time, we point out that this U(1) symmetry can be a linear combination of the $B-L$ and the SM hypercharge gauge symmetries. With a redefinition of $B-L$ charge of fermions, we find some interesting parameter spaces that not only satisfy the stability and cosmological production requirements of DM but can also be tested in future direct detection experiments such as superCDMS.

2 Stability of the Féeton DM

The SM can be extended with a $\mathrm{U}(1)_{B-L}$ gauge symmetry and its corresponding gauge boson A'. The related Lagraingain is,

$$\mathcal{L} = (D_\mu \Phi)^\dagger D^\mu \Phi - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \lambda \left(|\Phi|^2 - \frac{V_{B-L}^2}{2} \right)^2 + g_{B-L} q_{B-L} \bar{f} \gamma^\mu f A'_\mu. \tag{2.1}$$

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The covariant derivative D_μ is defined as $D_\mu \equiv \partial_\mu - i2g_{B-L}A'_\mu$ with the gauge coupling g_{B-L}, as the Higgs field Φ has a $B-L$ charge $q_{B-L}=2$. The spontaneous symmetry breaking gives the Higgs field Φ a vacuum expectation value (vev) V_{B-L}, its mass $m_\phi = \sqrt{2\lambda}V_{B-L}$, and a gauge boson mass $m_{A'} = 2g_{B-L}V_{B-L}$. Any fermions f with a $B-L$ charge q_{B-L} can couple to the gauge boson A' with a universal coupling strength g_{B-L}. The fermions f include not only the SM quarks with $B-L$ charge $q_{B-L}=1/3$ and leptons with $q_{B-L}=-1$, but also the heavy RHNs with $q_{B-L}=-1$ to cancel the gauge anomalies. Such a framework is self-consistent and well-motivated, as the three RHNs are important ingredients for generating the tiny neutrino masses via see-saw mechanism [13–17] and the baryon asymmetry in our Universe via leptongensis [18, 19]. In order for the standard leptongensis to work, the vacuum expectation value V_{B-L} should satisfy $V_{B-L} > 3\times 10^9$ [18, 19, 23], which gives the upper bound for the coupling g_{B-L} shown as the dashed purple line in figure 1. This upper limit can be greatly relaxed if we consider some other leptongensis scenarios, such as resonant leptogenesis [24, 25]. Furthermore, the gauge boson A' can be a natural candidate of DM in this minimal framework [20–22], called as féeton.

With the coupling to leptons, the féeton with a certain mass will decay. The decay rate is dominant by its decay channel to two active neutrinos as,

$$\Gamma_{A'} \simeq \frac{1}{8\pi} g_{B-L}^2 m_{A'}. \tag{2.2}$$

The required long lifetime for the féeton DM is guaranteed by the extremely small gauge coupling constant g_{B-L}. By conservatively assuming that the lifetime of féeton DM excesses ten times of the age of the universe, $\tau_{A'} > 150\,\text{Gyr}$, an upper bound on g_{B-L} can be derived, as shown by the black dashed line in figure 1. Consequently, the grey shaded region is excluded by the requirement of DM stability. Such a constraint on coupling is notably stringent, with $g_{B-L} \leq 10^{-16}$ even for light féeton with a mass $m_{A'} = 1\,\text{eV}$.

Actually, this extra unknown U(1) gauge symmetry can be in principle a linear combination of the canonical $\text{U}(1)_{B-L}$ symmetry and the SM $\text{U}(1)_Y$ symmetry, as both them are anomaly-free. All the $B-L$ charges of fermions can be redefined as $q'_{B-L} \equiv q_{B-L} + \alpha Y$ with a rotation factor α [26, 27]. In such a case, the SM Higgs field is charged under this redefined $\text{U}(1)'_{B-L}$ with $q'_{B-L} = \alpha/2$ and gives an additional contribution to féeton mass. As a result, we need to re-diagonalize the mass matrix of gauge bosons to obtain their new mass eigenstates and interacting currents. First, we write the mass terms of the gauge bosons on the basis of the $\text{U}(1)_Y$, the neutral component of $\text{SU}(2)_L$ and the original $\text{U}(1)_{B-L}$ as $V^T \equiv \begin{pmatrix} B & W^3 & A' \end{pmatrix}$,

$$\mathcal{L}_m = V^T \begin{pmatrix} \frac{1}{8}g'^2v^2 & -\frac{1}{8}gg'v^2 & \frac{1}{8}g'g_{B-L}v^2\alpha \\ -\frac{1}{8}gg'v^2 & \frac{1}{8}g^2v^2 & -\frac{1}{8}gg_{B-L}v^2\alpha \\ \frac{1}{8}g'g_{B-L}v^2\alpha & -\frac{1}{8}gg_{B-L}v^2\alpha & 2g_{B-L}^2v_{B-L}^2 + \frac{1}{8}g_{B-L}^2v^2\alpha^2 \end{pmatrix} V \tag{2.3}$$

with $g\,(g')$ being the gauge couplings of the SM SU(2) ($\text{U}(1)_Y$). Then, we utilize the Weinberg angle, $S_w = g'/\sqrt{g^2+g'^2}$ and $C_w = g/\sqrt{g^2+g'^2}$, to first diagonalize the B and W^3 field into the photon field $\tilde{A}$ and weak gauge boson $\tilde{Z}$ as an intermediate step,

$$\begin{pmatrix} \tilde{A} \\ \tilde{Z} \\ \tilde{A}' \end{pmatrix} = \begin{pmatrix} C_w & S_w & 0 \\ -S_w & C_w & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} B \\ W^3 \\ A' \end{pmatrix}. \tag{2.4}$$

The mass terms in this intermediate basis $\tilde{V}^T \equiv \left(\tilde{A}\ \tilde{Z}\ \tilde{A}'\right)$ becomes,

$$\mathcal{L}_m = \tilde{V}^T \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{1}{8}(g^2+g'^2)v^2 & -\frac{1}{8}\alpha g_{B-L}\sqrt{g^2+g'^2}v^2 \\ 0 & -\frac{1}{8}\alpha g_{B-L}\sqrt{g^2+g'^2}v^2 & 2g_{B-L}^2 v_{B-L}^2 + \frac{1}{8}g_{B-L}^2 v^2\alpha^2 \end{pmatrix} \tilde{V}. \tag{2.5}$$

One can see that the SM photon remains massless as expected. After the diagonalization of the remaining mass matrix for the intermediate $\tilde{Z}$ and $\tilde{A}'$, the mass eigenstates Z and A' are defined as,

$$\begin{pmatrix} Z \\ A' \end{pmatrix} \equiv \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} \tilde{Z} \\ \tilde{A}' \end{pmatrix} \tag{2.6}$$

with

$$\tan 2\xi = \frac{-\frac{1}{4}\alpha g_{B-L}\sqrt{g^2+g'^2}v^2}{\frac{1}{8}(g^2+g'^2)v^2 - 2g_{B-L}^2 v_{B-L}^2 - \frac{1}{8}g_{B-L}^2 v^2\alpha^2} \sim \frac{-2\alpha g_{B-L}}{\sqrt{g^2+g'^2}}. \tag{2.7}$$

With the above rotations, the interaction currents change as well. The interacting terms of fermions with gauge bosons are,

$$\mathcal{L}_I = J^\mu_{em}A_\mu + \left(\cos\xi J^\mu_{\tilde{Z}} + \sin\xi J^\mu_{\tilde{A}'}\right) Z_\mu + \left(-\sin\xi J^\mu_{\tilde{Z}} + \cos\xi J^\mu_{\tilde{A}'}\right) A'_\mu, \tag{2.8}$$

where $J^\mu_{\tilde{Z}}$ is the Z boson current in SM and $J^\mu_{\tilde{A}'}$ is the original féeton current before the redefinition. Firstly, one can observe that the neutrino-féeton coupling is independent of α,

$$\mathcal{L}_\nu = \left[-\frac{g}{2C_w}\sin\xi + g_{B-L}(-1-\frac{1}{2}\alpha)\cos\xi\right]\bar{\nu}_L\gamma^\mu\nu_L A'_\mu \approx -g_{B-L}\bar{\nu}_L\gamma^\mu\nu_L A'_\mu, \tag{2.9}$$

which means the decay width of féeton and the constraint from DM stability remain unchanged even after the charge redefinition. However, it is important to note that the coupling strength between electron and féeton is dependent of α as,

$$\begin{aligned} \mathcal{L}_e &= \left(g_{B-L}\cos\xi(-1-\frac{1}{2}\alpha) - g\sin\xi\frac{-\frac{1}{2}+S_w^2}{C_w}\right)\bar{e}_L\gamma^\mu e_L X^m_\mu \\ &\quad + \left(g_{B-L}\cos\xi(-1-\alpha) - g\sin\xi\frac{S_w^2}{C_w}\right)\bar{e}_R\gamma^\mu e_R X^m_\mu \\ &= \left(-1-C_w^2\alpha\right)g_{B-L}\bar{e}\gamma^\mu e A'_\mu. \end{aligned} \tag{2.10}$$

With a typical α, such as $\alpha = 2.6$, the $B-L$ charge of electron changes from -1 to -3, leading to a enhancement of the féeton-electron interaction cross section by one order of magnitude. Due to this redefinition of the $B-L$ charge, the detection capability of this model will also be enhanced by the DM direct detection experiments, as we will discuss later.

3 Cosmic production of the Féeton DM

However, a crucial issue of the féeton DM is its cosmological production, as it is very difficult to produce the féeton in the early universe due to the small gauge coupling constant. Nevertheless, two natural mechanisms have been proposed for sufficient vector boson DM productions:

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the decay of cosmic strings associated with U(1) gauge symmetry breaking [28, 29] , and the quantum fluctuations during the inflation [30]. We shall discuss their applications to the féeton DM production as follows.

The féeton DM, as the gauge boson of the $U(1)_{B-L}$ gauge symmetry, gains its mass from the Higgs mechanism. The dark Higgs field Φ obtains a vacuum expectation value V_{B-L}, and the $U(1)_{B-L}$ symmetry is spontaneously broken. Once the symmetry breaking happens after inflation, cosmic string networks appear [31] and their subsequent decay produce the féeton DM relic abundance Ω_f,

$$\Omega_f \simeq 0.12 \left(\frac{\xi}{5.7}\right) \left(\frac{m_{A'}}{1\,\text{keV}}\right)^{1/2} \left(\frac{V_{B-L}}{1.6\times 10^{10}\,\text{GeV}}\right)^2, \tag{3.1}$$

can be consistent with the observed value. The average string number per Hubble volume ξ can be obtained from simulations [32, 33],

$$\xi = 0.15 \log\left(\frac{m_\Phi}{m_{A'}}\right) = 0.15 \log\left(\frac{\sqrt{2\lambda} V_{B-L}}{m_{A'}}\right) \tag{3.2}$$

The corresponding parameters that generate the correct relic density by taking $\lambda = 1/2$ are shown as the yellow solid line in figure 1. Note that there is an $\mathcal{O}(1)$ uncertainty in the relic density calculation, which arises from the uncertainties in the cosmic string simulation.[1] This means that the parameter space is actually a band centered around the yellow line with a width of one order.

The other possibility for the féeton DM production is the production of massive vector boson from the quantum fluctuations during inflation. The massive vector field is initially sub-horizon and evolves to become super-horizon modes during inflation. Subsequently, they re-enter the horizon during radiation domination to be cosmic relics. In such a scenario, the relic density of féeton is precisely determined by its mass and the Hubble scale of inflation H_I [30],

$$\Omega_{A'} = 0.3 \sqrt{\frac{m_{A'}}{1\,\text{keV}}} \left(\frac{H_I}{10^{12}\,\text{GeV}}\right)^2. \tag{3.3}$$

It is required that the spontaneous breaking of $B-L$ gauge symmetry occurs before or during inflation, leading to $V_{B-L} > H_I$. Taking H_I as a lower bound for V_{B-L}, the above relic density formula has an same scaling of $m_{A'}$ and V_{B-L} as the cosmic string case eq. (3.2). As a result, the upper bound line for féeton coupling g_{B-L} as a function of $m_{A'}$ to generate the right relic density (red solid) is parallel to that of the cosmic string production but with around 2 orders smaller. The larger vev V_{B-L}, or equivalently, smaller coupling g_{B-L} area (red shaded region) can also generate the correct DM relic density.

4 Direct detection of the Féeton DM

Although the requirements for stability and relic density have predicted a very small féeton DM coupling, our scenario can still be tested by future direct detection experiments.

[1] We would acknowledge the communication with N. Kitajima and K. Nakayama on this point.

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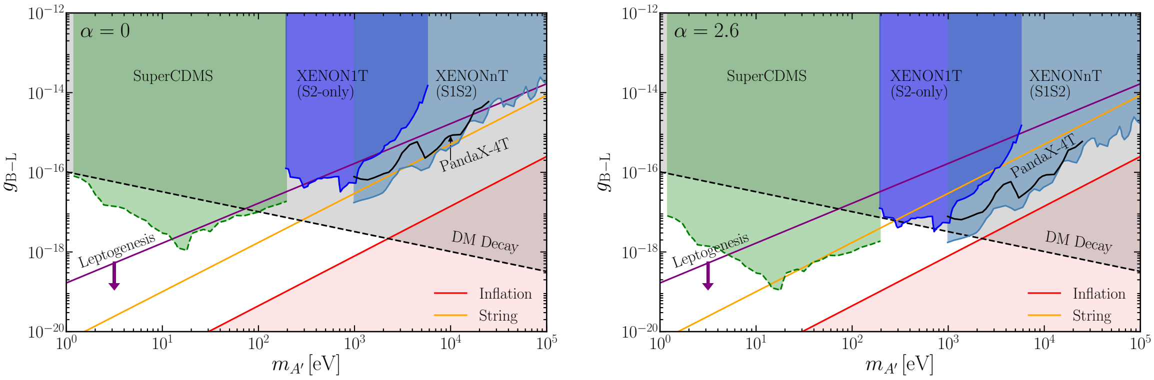

Figure 1. The parameter space of féeton DM for generating the correct relic density via inflation production (red shaded region) and cosmic string decay (orange solid line with one order of uncertainty). The gray shaded region is excluded since the corresponding lifetime of the féeton DM is shorter than ten times of the age of Universe, $\tau_{\mathfrak{f}} < 150\,\text{Gyr}$, due to DM stability. The blue shaded regions are the current constraint from the XENON1T (S2-only) and XENONnT (S1S2) experiments [34–36] while the green region is the projected limit in future SuperCDMS experiments [37]. The black solid line is the constraint from PandaX-4T [38]. All these direct detection constraints are dependent of the charge redefinition parameter α. The left panel corresponds to the case of $\alpha = 0$ and the right panel the case of $\alpha = 2.6$.

The féeton DM can be absorbed by the electron targets in the DM direct detection experiments via the leading process $e + A' \to e + \gamma$ [39–47]. With the total DM mass transferred into the kinetic energy of the final states, such an absorption process allows a lower mass threshold for DM detection [47–49]. In the Xenon-based DM direct detection experiments, such as Xenon [34–36], PandaX [38, 50], and LZ [51, 52], the most outer layer electrons of Xenon atom has a binding energy of $\sim 10\,\text{eV}$. Due to the energy conservation, the féeton DM with a mass larger than 10 eV is allowed to be absorbed and ionized the electrons. Therefore, these experiments place constraints on féeton coupling above the féeton mass $m_{A'} \sim 10\,\text{eV}$, and become the strongest terrestrial experimental constraints beyond $\sim 200\,\text{eV}$. The stringent constraint from XENON1T (S2 only) [34] and XENONnT (S1S2) experiments [36] are shown as the blue regions in the left panel of figure 1. The PandaX-4T experiment currently has a better S2-only sensitivity [53, 54]. Although the experimental testability has reached the Leptogenesis and string production lines, such a parameter space is already disfavored from the stability requirement for DM.

The next-generation SuperCDMS experiment, which will be developed in SNOLAB [37], is expected to have a lower detection threshold and better projected sensitivity in the low mass range. The detection threshold of a phonon detector is determined by the band gap of the materials it is composed of. For gemanium (Ge), which is planned to be used in the SuperCDMS project, the threshold can be lowered to 0.67 eV. The projected sensitivity of the SuperCDMS experiment for the féeton absorption process is shown by the green region in the figure 1. It provides the strongest constraints on féeton coupling in the mass range from $\sim 1\,\text{eV}$ to $\sim 200\,\text{eV}$. This projected constraint can reach the féeton DM region below the black dashed line, and surpass the upper limit of canonical leptogenesis as well in the féeton mass range $\sim (10, 100)\,\text{eV}$.

All these direct detection constraints become stronger if the $U(1)_{B-L}$ symmetry contains a linear combination with the SM $U(1)_Y$ symmetry, where $\alpha \neq 0$. As previously stated, if $\alpha = 2.6$, the charge of the electron, or equivalently, its coupling with féeton, increases by three times. As a result, the cross section of féeton absorption increases by a factor of ~ 10, thereby strengthening the constraints on the féeton model with this α by an order of magnitude in direct detection experiments. We show these enhanced limits in the right panel of figure 1. One can see the future SuperCDMS can test the féeton DM parameter space which is consistent with the cosmic string production in the mass range $m_{A'} \subset (10, 200)\,\mathrm{eV}$. The future Xenon-based detectors, with tenfold increased exposure and reduced backgrounds, can even get a better sensitivity [55, 56], having the possibility to test the inflation production of féeton DM with a mass around $m_{A'} \sim 10^3\,\mathrm{eV}$.

5 Conclusions and discussions

What is dark matter? This is one of the most important questions in modern physics. There is no universal method for the detection of DM; it must rely on the mass and interaction type of DM predicted by DM models. Therefore, clearly defined, theoretically well-motivated DM candidates are of great importance. Currently, our strategy is to search for DM candidates that can address issues in the SM. Among the most popular are WIMPs and the axion. WIMPs can be predicted by a broad range of new physics models. One well-motivated class is supersymmetry model, which was initially proposed to unify all interactions and can address the hierarchy problem in the SM [57–59]. However, so far, no supersymmetric particles have been discovered at colliders, and direct detection of DM has placed strong constraints on WIMPs. On the other hand, the proposal of the axion aimed to theoretically solve the strong CP problem, but it also suffers from more severe high-quality problem [60, 61]. And there are alternative solutions to the strong CP problem that do not require the introduction of the axion [62–68].

Compared to theoretical puzzles like the hierarchy problem and the strong CP problem, phenomena beyond the SM such as neutrino masses and baryon asymmetry pose more concrete phenomenological questions. Within the framework of the seesaw mechanism, which introduces three heavy Majorana RHNs, both of these issues can be effectively addressed. Moreover, this framework can also motivate the existence of a new $B-L$ U(1) gauge symmetry, incorporating the corresponding gauge boson A'. As long as the gauge coupling is sufficiently small to ensure the stability of A', it can naturally become DM. We call it féeton DM. This DM candidate predicted from the simple and elegant extension of SM deserves more attention.

In this paper, we revisit the physics of féeton DM, and show the viable parameter space required from the stability of DM. After that, we review the cosmic production of féeton DM via cosmic string decay and inflation. In this canonical féeton DM model, the most parameter space the DM direct detection can constrain is already excluded due to the DM decay. The future SuperCDMS, however, can reach the féeton DM region, which is consistent with the canonical leptogenesis with $V_{B-L} > 3 \times 10^9\,\mathrm{GeV}$. More importantly, we first point out the freedom of the definition of $B-L$ charge, $q'_{B-L} \to q_{B-L} + \alpha Y$, since this U(1) gauge symmetry can be a linear combination of the $B-L$ and the SM hypercharge gauge symmetries. With this redefinition, the coupling between electron and féeton can be enhanced, leading to a stronger limit from DM direct detection. In the case of $\alpha = 2.6$, as the example in our paper, all the direct detection constrained is enhanced by one order of magnitude. In such a scenario, the future SuperCDMS will have the capability to test the cosmic string production of féeton DM in the mass range $m_{A'} \subset (10, 200)\,\text{eV}$ while the future Xenon-based detectors, such as the Xenon-nT, PandaX, and LZ, have a chance to test the inflation production of féeton DM with a mass $m_{A'} \sim 1\,\text{keV}$.

For the féeton DM lighter than 1 eV, there are also some experimental proposals, such as the Josephson junction current [69, 70] and molecule excitations [71], to detect them. However, the predicted coupling from DM production is too small to be reached. In even lighter mass ranges, like $m_{A'} < 10^{-5}\,\text{eV}$, fifth force experiments have imposed very strong constraints [72–76].

Finally, we should comment on the serious difference between the féeton DM model and the dark photon DM model. The dark photon DM couples to the electron only through the kinetic mixing term between the dark photon and the SM photon [77]. Thus, we do not have any prediction for the detection experiments as its kinetic mixing ϵ is a free parameter, which is independent from the DM mass and the vaccum expectation value of the dark gauge symmetry breaking scale. It is crucial the féeton mass is given by $m_{A'} = 2g_{B-L}V_{B-L}$. This is the reason why we have a certain prediction for the detection of the féeton DM in the future direct detection experiments.

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