Dark photon portal dark matter with the 21-cm anomaly

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A strong absorption profile centred at 78 MHz was reported by the EDGES Collaboration, which indicates the hydrogen gas being colder than expected. It could be signatures of a non-gravitational interaction between normal matter and dark matter (DM), and a potential explanation is that a small fraction of millicharged DM scatters with normal matter, with masses of millicharged DM in tens MeV and the scattering cross section ∝ v−4. To obtain the small fraction of millicharged DM and meanwhile being tolerant with by the constraints, the dark photon portal scalar and vector millicharged DM are explored in this paper. We consider that the mass of dark photon is slightly above twice of the millicharged DM mass, and thus the millicharged DM predominantly annihilates in p-wave during the freeze-out period, with the annihilation being enhanced near the resonance. The dark photon mainly decays into millicharged DM, and couplings of dark photon with SM particles could be allowed by the lepton collision experiments. The corresponding parameter spaces are derived. The future lepton collision experiment can be employed to search for millicharged DM via the production of the invisible dark photon.

I. INTRODUCTION

In the Universe, about 84% of the cosmological matter density is contributed by dark matter (DM) [1], while little has been known about particle properties of DM by now. Recently, an absorption profile around 78 MHz in the sky-averaged spectrum was reported by the EDGES Collaboration [2], and the magnitude of the absorption was enhanced with 3.8σ discrepancy. This enhancement would indicate the hydrogen gas being colder than expected, and it may be signatures of non-gravitational interactions between normal matter and DM from the cosmic dawn [2–6].

To cool the hydrogen gas via the scatterings between DM and hydrogen, residual electrons and protons, the mass of DM should be not much heavier than the hydrogen mass.1 Meanwhile, to explain the absorption profile, velocity-independent scatterings seem to be in tension with the cosmic microwave background (CMB) observation, and velocity-dependent scatterings are available [3, 4], with the cross sections ∝ v−4. Possible new light mediators with masses ≲ 10−3 eV are not favored by constraints from CMB and the big bang nucleosynthesis [1, 10–13], and a feasible scenario is that a small fraction (about 0.003−0.02) of DM is millicharged (DM electric charge/e ∼ 10−6 − 10−4) [12–15], with DM mass about 10−80 MeV and photon as the mediator in the scattering.

To avoid the overproduction of DM in the early universe, new annihilation mechanisms are needed to obtain the required DM relic abundance. Besides DM being millicharged, here we consider that DM is also dark charged, which thus can have other couplings to the standard model (SM) sector via the photon-dark photon kinetic mixing \( \frac{1}{2} \epsilon \cos \theta W^\mu \partial_\mu A'^\nu \) (see e.g., Refs. [16–22] for more), where \( A' \) is the dark photon field. In addition, the CMB observation [1, 23] and the 21-cm absorption profile from the cosmic dawn [2, 24] set stringent on s-wave annihilations of DM with masses in the MeV scale. A possible way is that the millicharged DM predominantly annihilates in p-wave during the freeze-out period, and thus the scalar and vector DM with masses being lighter than the dark photon are of our concern.

Due to a small fraction of DM being millicharged, the couplings of dark photon with SM particles may be not very small, and this will be restricted by the

1 For other scenarios, such as modifying the radio background, see e.g., Refs. [7–9].
lepton collision experiments [25–28]. Here we consider the case that the mass of dark photon is slightly above twice of the millicharged DM mass. In this case, dark photon can mainly decay into millicharged DM. The annihilations of millicharged DM are significantly enhanced near the resonance, and the couplings of dark photon with SM particles could be allowed by the lepton collision experiments. The corresponding parameter space will be derived in this paper.

II. INTERACTIONS AND TRANSITIONS

Here we consider the photon and dark photon $A'$ mediate the transitions between millicharged DM and SM sector. The interaction of $A'$ boson with SM charged fermion is taken as

$$L^S_M = e e A'_\mu J^\mu_{em},$$

For scalar (vector) millicharged DM $\phi (V)$, the electric charge is taken as $e e (\varepsilon \sim 10^{-6} - 10^{-4} [12–14])$, and the dark charge is $e_D$. Here we focus on the case that the main decay products of $A'$ are invisible, i.e., $A'$ mainly decaying into DM pairs $\phi \phi^*$ with the mass $2m_\phi (2m_V) < m_{A'}$. During millicharged DM freeze-out, the required large annihilation cross section is mainly contributed by $A'$. For the DM mass range of concern, the p-wave annihilation process $\phi \phi^* (VV^*) \rightarrow A' \rightarrow e^+ e^-$ is predominant during DM freeze-out. To enhance DM annihilations, here we consider that $m_{A'}$ is slightly above $2m_\phi (2m_V)$, and thus the annihilations of DM can be significantly enhanced close to the resonance.

Now we formulate the millicharged DM annihilations mediated by $A'$. For scalar millicharged DM $\phi$, the annihilation cross section of the process $\phi \phi^* \rightarrow A' \rightarrow e^+ e^-$ is

$$\sigma_{\text{ann}} v_r = \frac{1}{2} \frac{e_D^2 e^2 c^2}{12 \pi (s - 2m_\phi^2)} \frac{s(s - 4m_\phi^2)}{(s - m_{A'}^2)^2 + m_{A'}^2 \Gamma_{A'}^2},$$

where $v_r$ is the relative velocity of the annihilating DM pair, and the factor $\frac{1}{2}$ is included here for the required $\phi \phi^*$ pair in DM annihilations. $s$ is the total invariant mass squared, with $s = 4m_\phi^2 + m_\phi^2 v_r^2 + O(v_r^4)$ in the nonrelativistic limit. Here the electron mass is negligible for the DM mass of concern. $\Gamma_{A'}$ is the decay width of $A'$, with

$$\Gamma_{A'} \approx \frac{e_D^2}{48 \pi} m_{A'} (1 - \frac{4m_\phi^2}{m_{A'}^2})^2.$$

For vector millicharged DM $V$, the annihilation cross section of the process $VV^* \rightarrow A' \rightarrow e^+ e^-$ is

$$\sigma_{\text{ann}} v_r \approx \frac{1}{2} \frac{e_D^2 e^2 c^2}{54 \pi (s - 2m_V^2)} \frac{13s(s - 4m_V^2)}{(s - m_{A'}^2)^2 + m_{A'}^2 \Gamma_{A'}^2}.$$ (4)

In the nonrelativistic limit, one has $s = 4m_V^2 + m_{A'}^2 v_r^2 + O(v_r^4)$. The corresponding $\Gamma_{A'}$ is

$$\Gamma_{A'} \approx \frac{e_D^2}{48 \pi} m_{A'} (1 - \frac{4m_V^2}{m_{A'}^2})^2 (3 + \frac{5m_{A'}^2}{m_{V}^2} + \frac{m_{A'}^4}{4m_V^4}). (5)$$

Here we give a brief discussion about the photon mediated transitions. The annihilation mode $\phi \phi^* (VV^*) \rightarrow \gamma \rightarrow e^+ e^-$ is a p-wave process, which is suppressed by $\varepsilon^2$. The annihilation mode $\phi \phi^* (VV^*) \rightarrow \gamma \gamma$ is a s-wave process, while this process is deeply suppressed by $\varepsilon^4$. Thus, we can neglect the photon’s contribution during millicharged DM freeze-out. For the millicharged DM of concern, the corresponding energy injection from the process $\phi \phi^* (VV^*) \rightarrow \gamma \gamma$ is allowed by the CMB observation [1, 23] and the 21-cm absorption profile [2, 24].

III. NUMERICAL ANALYSIS

As given by the Introduction, to cool the hydrogen gas indicated by the EDGES observation, the fraction of millicharged DM $f_{DM}$ is about 0.003–0.02, with DM mass $\sim 10–80$ MeV. For teens MeV DM, the annihilation products of DM could heat the electron-photon plasma in the early universe after the electron neutrino decoupling, and this would reduce the effective number of the relativistic neutrinos $N_{eff}$. Considering the recent Planck observations on $N_{eff}$ [1], one has the relation of the DM mass [29]: $m_\phi \gtrsim 10.4$ MeV for scalar DM, and $m_V \gtrsim 13.6$ MeV for vector DM. Thus, the following mass range of the millicharged DM is adopted
here: $10.4 \lesssim m_\phi \lesssim 80$ MeV for scalar DM, and $13.6 \lesssim m_V \lesssim 80$ MeV for vector DM.

The total relic density of DM is $\Omega_D h^2 = 0.1197 \pm 0.0042$ [1]. For scalar (vector) millicharged DM, to obtain the large annihilation cross section at the freeze-out epoch indicated by the small $f_{\text{DM}}$, we consider the annihilation being close to the resonance.

Note $\xi = m_{A'}/2m_\phi$ ($m_{A'}/2m_V$), and here $\xi$ is slightly above 1. For a given coupling parameter $e_D^2 \epsilon^2$, the annihilation cross section of millicharged DM will be increased with the reducing of $\xi$’s value (here the value $\xi - 1 > 0$). With the perturbative requirement, one has $e_D^2 \lesssim 4\pi$. In addition, the recent lepton collision experiments, such as BaBar [28] and NA64 [27], set an upper limit on $\epsilon$ in the search of the dark photon’s invisible decay, i.e., $\epsilon \lesssim 10^{-7}$ [13, 34], accounting for the terrestrial effect when a charged particle penetrating the earth. Moreover, due to the magnetic fields in the Milky Way, the millicharged DM is expected to be evacuated from the Galactic disk [3, 35, 36], and hence will be absent from DM direct detections. Thus, DM with the millicharge parameter $\epsilon$ of concern is allowed by the direct detection experiments (see e.g., Ref. [13].
FIG. 2. The value of $\epsilon$ as a function of $m_{A'}$ for $\xi = 1.16, 1.1$ and 1.04 when considering the $f_{\text{DM}}$ of millicharged DM indicated by the 21-cm anomaly. The value $e_D = 1$ is adopted here. For the band of a given $\xi$, the upper, lower limits are for $f_{\text{DM}} = 0.003, 0.02$ respectively. The upper limit of $\epsilon$ with constraints from NA64 [27] and BaBar [28], and the region preferred by the muon g−2 [30] are denoted in the figure.

IV. CONCLUSION AND DISCUSSION

The dark photon portal scalar, vector millicharged DM was studied in this paper, which could cool the gas and produce the 21-cm anomaly absorption via the scattering. To obtain the small fraction $f_{\text{DM}}$ of millicharged DM, we consider that the annihilations are mainly mediated by the dark photon during millicharged DM freeze-out, with the annihilations near the resonance and the parameter $\xi$ being slightly above 1. The annihilation mediated by the dark photon is a p-wave process, and thus it is tolerant by the constraints from CMB and the 21-cm absorption profile.

The value of $\xi$ was derived for the required fraction $f_{\text{DM}} = 0.003–0.02$, with $10.4 \lesssim m_\phi \lesssim 80$ MeV for scalar millicharged DM, and $13.6 \lesssim m_V \lesssim 80$ MeV for vector millicharged DM. For a given coupling parameter $e_D^2\epsilon^2$, a smaller fraction $f_{\text{DM}}$ requires a smaller $\xi - 1$ value. For a given $\xi$, the range of $\epsilon$ was derived for the $f_{\text{DM}}$ of millicharged DM indicated by the 21-cm absorption anomaly. The upper limit of $\epsilon$ was considered with the recent results of NA64 [27] and BaBar [28]. The millicharged DM with the $\epsilon$ of concern could be absent in direct detection experiments. The lepton collision experiments can be employed to do the work of searching for millicharged DM via the production of the invisible dark photon, or the value of the parameter $\epsilon$ would be further restricted by the experiments. The lepton collision experiment does well in the search of $A'$ for the case of a small $f_{\text{DM}}$ and a large $\xi$. We look forward to the search of millicharged DM at future lepton collision experiments.

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