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Dark photon portal dark matter with the 21-cm anomaly

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Abstract A strong absorption profile was reported by the EDGES Collaboration, which indicates the hydrogen gas being colder than expected. It could be signatures of non-gravitational interactions between normal matter and dark matter (DM), and a possible explanation is that a small fraction of millicharged DM scatters with normal matter, with the DM mass in tens of MeV. To obtain the small fraction of millicharged DM and meanwhile being tolerant as regards the constraints, the dark photon portal scalar and vector millicharged DM are explored in this paper. We consider the mass of dark photon to be slightly above twice 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 the dark photon with SM particles could be allowed by the lepton collision experiments. The corresponding parameter spaces are derived. Future lepton collision experiments can be employed to search for millicharged DM via the production of the invisible dark photon.

1 Introduction

In the universe, about 84% of the cosmological matter density is contributed by dark matter (DM) [1], while little has become known about the 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 to be 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 $\propto v^{-4}$. Possible new light mediators with masses $\lesssim 10^{-3}$ 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 (a DM particle carries an electric charge ηe with $\eta \sim 10^{-6}$–10^{-4}) [12–15], with a DM mass about 10–80 MeV and the photon as the mediator in the scattering of cooling the hydrogen. For the vector–vector current scattering being mediated by the photon (in the nonrelativistic limit), the parameter spaces are nearly the same not only for scalar and fermionic millicharged DM [12], but also for vectorial millicharged DM (see, e.g., Ref. [16]).

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 DM to also be dark charged, which can have other couplings to the standard model (SM) sector, e.g., via the photon–dark photon kinetic mixing $\frac{1}{2}(\epsilon/\cos\theta_W)F_{\mu\nu}A'^{\mu\nu}$, where A' is the dark photon field (see, e.g., Refs. [17–25]). In addition, the CMB observation [1,26] and the 21-cm absorption profile from the cosmic dawn [27,28] set stringent constraints 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 the dark photon with SM particles may be not very small, and this will be restricted by the lepton collision

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experiments [29–32]. Here we consider the case that the mass of the dark photon is slightly above twice the millicharged DM mass. In this case, the dark photon can mainly decay into millicharged DM. The annihilations of millicharged DM are significantly enhanced near the resonance, and the couplings of the dark photon with SM particles could be allowed by lepton collision experiments. The corresponding parameter space will be derived in this paper.

2 Interactions and transitions

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

$$\mathcal{L}_i^{SM} = e\epsilon A'_\mu J_{\text{em}}^\mu. \tag{1}$$

For scalar (vector) millicharged DM ϕ (V), the electric charge is taken as ηe ($\eta \sim 10^{-6}$–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 decays into DM pairs $\phi\phi^*$ (VV^*) with the mass $2m_\phi(2m_V) < m_{A'}$. To enhance DM annihilations during millicharged DM freeze-out, here we consider $m_{A'}$ to be slightly above $2m_\phi$ ($2m_V$). Thus, the annihilations of DM can be significantly enhanced close to the resonance, and 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^*) $\to A' \to e^+e^-$ is predominant during DM freeze-out.

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

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

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 $s = 4m_\phi^2 + m_\phi^2 v_r^2 + \mathcal{O}(v_r^4)$ 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

$$\Gamma_{A'} \approx \frac{e_D^2}{48\pi} m_{A'} \left(1 - \frac{4m_\phi^2}{m_{A'}^2}\right)^{\frac{3}{2}}. \tag{3}$$

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

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

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

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

Here we give a brief discussion of the photon mediated transitions. The annihilation mode $\phi\phi^*$ (VV^*) $\to \gamma \to e^+e^-$ is a p-wave process, which is suppressed by the millicharge parameter η^2, and the corresponding thermally averaged annihilation cross section is in the range of about 10^{-32}–10^{-26} cm^3/s (much smaller than the value required by the small fraction of millicharged DM). The annihilation mode $\phi\phi^*$ (VV^*) $\to \gamma\gamma$ is a s-wave process, and this process is deeply suppressed by η^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^*) $\to \gamma\gamma$ is allowed by the CMB observation [1,26] and the 21-cm absorption profile [2,27].

3 Numerical analysis

As mentioned in 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 of 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 following relation for the DM mass [33]: $m_\phi \gtrsim 10.4$ 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_{DM}, we consider the annihilation to be close to the resonance.

Note $\xi = m_{A'}/2m_\phi$ ($m_{A'}/2m_V$), and here ξ 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 reduction of the ξ's value (here the value $\xi - 1 > 0$). With the perturbative requirement, one has $e_D^2 < 4\pi$. In addition, the recent lepton collision experiments, such as BaBar [32] and NA64 [31], set an upper limit on ϵ in the search of the dark photon's invisible decay, i.e., $\epsilon \lesssim (10^{-4}$–$10^{-3})$ for $m_{A'}$ in a range of 20–200 MeV. Thus, a typical upper limit $e_D \epsilon \lesssim 10^{-4}$ is adopted here. In this case, to obtain the fraction f_{DM} of millicharged DM indicated by the EDGES
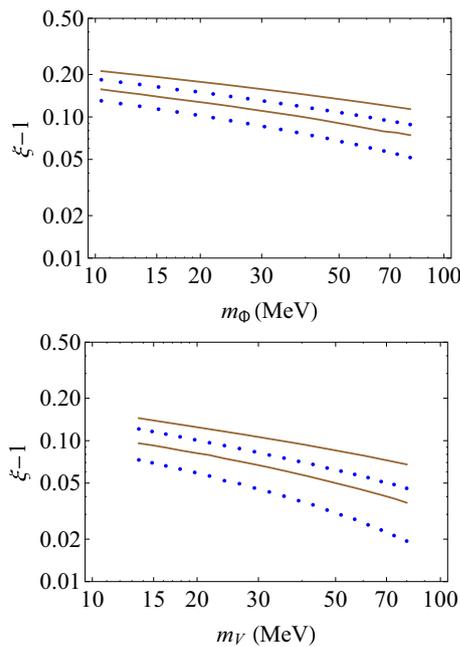
Fig. 1 The required value of $\xi - 1$ for scalar and vector millicharged DM with the EDGES observation. The coupling parameter $e_D \epsilon = 10^{-4}$ is taken here. The mass range of the scalar millicharged DM is $10.4 \lesssim m_\phi \lesssim 80$ MeV, and $13.6 \lesssim m_V \lesssim 80$ MeV for vector millicharged DM. The dotted, solid curves are for the case of $e_D = 1, 0.5$, respectively. In each type of curve (dotted, solid curves), the upper (lower) one corresponds to $f_{DM} = 0.02 (0.003)$, respectively

experiment, the corresponding ξ required is shown in Fig. 1 (see Appendix for the calculation), with $e_D \epsilon = 10^{-4}$ for scalar and vector millicharged DM. The dotted (solid) curves are for the value $e_D = 1 (0.5)$ being adopted, respectively, and the upper (lower) one in each type of curve corresponds to $f_{DM} = 0.02 (0.003)$, respectively. For a given $e_D^2 \epsilon^2$, a smaller fraction f_{DM} corresponds to a smaller $\xi - 1$ value.

The invisible dark photon (mainly decaying into scalar, vector millicharged DM) may be produced at the lepton col-

lision experiments [29–32], or the value of the kinetic mixing parameter ϵ would be restricted by the experiments. For a given ξ, to obtain the fraction of millicharged DM indicated by the 21-cm absorption, the corresponding range of ϵ is derived, as shown in Fig. 2, with $\xi = 1.16, 1.1$ and 1.04, and $e_D = 1$. For a given ξ, the upper (lower) limit of each band is for $f_{DM} = 0.003 (0.02)$, respectively. The recent results of NA64 [31] and BaBar [32] set an upper limit on ϵ. It can be seen that, for $\xi = 1.16$, f_{DM} in the range of about 0.003–0.02 is allowed for scalar millicharged DM, while the parameter space for a small fraction of f_{DM} is excluded and f_{DM} close to 0.02 is left for vector millicharged DM. The lepton collision experiment does well in the search of A' for the case of a small f_{DM} and a large ξ. The parameter spaces can be tested at future experiments, such as Belle II [35] and the Light Dark Matter eXperiment (LDMX) [36].

Here we give a brief discussion of the detection of millicharged DM by underground experiments. For tens of MeV DM, the results of XENON10 [37,38] and COHERENT [39] seem to be sensitive for the scattering mediated by massless mediators (or the mediator's mass is very tiny). However, for the millicharged DM of concern, the exclusion region is feasible for the millicharge parameter $\eta \lesssim 10^{-7}$ [13,40], accounting for the terrestrial effect when a charged particle penetrates the earth. Moreover, due to the magnetic fields in the Milky Way, the millicharged DM is expected to be evacuated from the Galactic disk [3,41,42], and hence will be absent from DM direct detections. Thus, the millicharged DM of concern can be allowed by direct detections (see, e.g., Ref. [13]).

4 Conclusion and discussion

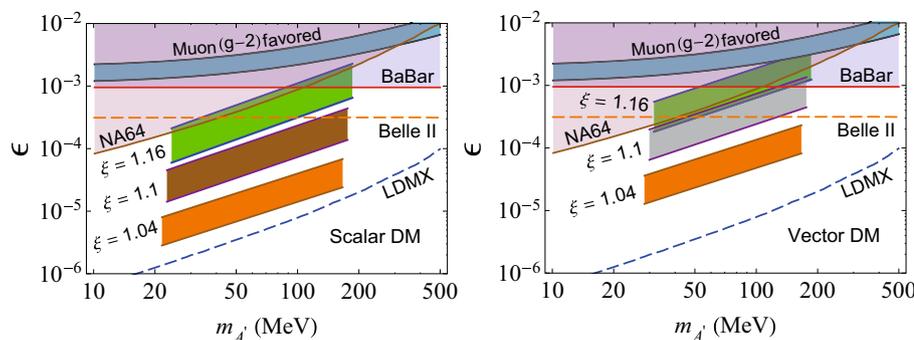The dark photon portal scalar/vector millicharged DM were studied in this paper, which could cool the gas and produce

Fig. 2 The value of ϵ as a function of $m_{A'}$ for scalar and vector millicharged DM with $\xi = 1.16, 1.1$ and 1.04. Here $e_D = 1$ is adopted. For the band of a given ξ, the upper (lower) limit is for $f_{DM} = 0.003 (0.02)$, respectively, with the range of f_{DM} indicated by the 21-cm anomaly. The upper limit of ϵ has constraints from NA64 [31] and BaBar [32],

and the region preferred by the muon $g - 2$ [34] is denoted in the figure. The upper and lower dashed curves are the expected sensitivity of Belle II 20 fb^{-1} [35] and the ultimate reach of Light Dark Matter eXperiment (LDMX) [36], respectively

the 21-cm anomaly via photon mediated scattering. To obtain the small fraction f_{DM} of millicharged DM, we consider the annihilations to be mainly mediated by the dark photon during millicharged DM freeze-out, with the annihilations near the resonance and the parameter ξ being slightly above 1. The annihilation mediated by the dark photon is a p-wave process, and thus it is tolerated by constraints from CMB and the 21-cm absorption profile.

The value of ξ was derived for the required fraction $f_{DM} = 0.003$–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_{DM} requires a smaller $\xi - 1$ value. For a given ξ, the range of ϵ was derived for the f_{DM} of millicharged DM indicated by the 21-cm absorption. The DM with the millicharge parameter η of concern could be absent in direct detection experiments. The lepton collision experiment does well in the search of millicharged DM via the production of the invisible dark photon, such as Belle II and LDMX, especially for the case of a small f_{DM} and a large ξ. We look forward to the search of millicharged DM at future lepton collision experiments.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: All the necessary data are explicitly presented in this paper. Requests for additional information, please contact with the corresponding author.]

Appendix: f_{DM} and the parameter ξ

The relic density of millicharged DM is $f_{DM}\Omega_D$. For thermal freeze-out millicharged DM at temperature T_f, f_{DM} can be set by the thermally averaged annihilation cross section $\langle \sigma_{ann} v_r \rangle$ via the relation [43]

$$f_{DM}\Omega_D h^2 \simeq \frac{1.07 \times 10^9 \text{ GeV}^{-1}}{J_{ann} m_{Pl} \sqrt{g_*}}, \tag{A1}$$

with

$$J_{ann} = \int_{x_f}^{\infty} \frac{\langle \sigma_{ann} v_r \rangle}{x^2} dx, \tag{A2}$$

and the parameter x_f is $x_f = m_\phi / T_f$ (m_V / T_f). Substituting $m_{A'} = 2m_\phi \xi$ $(2m_V \xi)$ into $\langle \sigma_{ann} v_r \rangle$, the relation between ξ and f_{DM} can be obtained.

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