PHYSICAL REVIEW D **105,** L091903 (2022)

Letter

New way to limit the interaction of dark matter with baryons

Abraham Loeb[*]

Department of Astronomy, Harvard University, 60 Garden Street, Cambridge, Massachusetts 02138, USA

(Received 29 November 2021; revised 10 February 2022; accepted 19 May 2022; published 31 May 2022)

Recently, there has been renewed interest in limiting the interaction between dark matter particles and known particles. I propose a new way to set upper limits on the coupling of ions or electrons to dark matter particles of arbitrary mass, based on Faraday's Law in a spinning conductor.

DOI: 10.1103/PhysRevD.105.L091903

I. INTRODUCTION

The nature of dark matter (DM) is unknown. One way to unravel the properties of DM particles is through their interaction with Standard Model particles, such as protons or electrons. Searches for weakly interacting massive particles by direct detection experiments have set strong bounds at GeV to TeV mass scales [1]. Lighter DM particle candidates with masses below GeV are well-motivated in a variety of particle physics scenarios [2–5]. However, the search for sub-GeV DM particles in traditional direct detection experiments is limited by the suppressed momentum transfer in nuclear recoil. Cosmological searches for light DM particles complements direct detection experiments for DM particles down to keV masses [6–12].

The existing upper limits on the cross-section for DM particles with protons were summarized recently in Fig. 1 of Ref. [13], extending down to values of $\sim 10^{-30}$ cm^2 for DM particle masses $m_{\rm dm} \sim 1$ keV.

Here, I consider a novel way to limit the proton-DM coupling based on the magnetic field generated in a spinning conductor. For pedagogical purposes, I illustrate the method in the context of the interstellar medium of the Milky Way galaxy, although its most powerful implementation should be in dedicated laboratory experiments.

II. INDUCED MAGNETIC FIELD

The interstellar gas of the Milky Way galaxy is organized into a thin disk with a flat rotation curve of circular velocity, $v_{\rm c} \sim 240$ km s^{-1} [14]. The ionized component of the gas is composed primarily of electrons and protons [15,16]. The Galactic disk is immersed in a DM halo with a characteristic mass density, $\rho_{\rm dm} \sim 0.5$ GeVcm^{-3}, in the vicinity of the Sun [17].

For a proton-DM cross-section σ, the proton-DM collision frequency is: $\nu_{\rm p-dm} \sim (\rho_{\rm dm}/m_{\rm dm})\mu\sigma v_{\rm c}$, where the reduced mass $\mu m_{\rm p} = (m_{\rm dm} m_{\rm p})/(m_{\rm dm} + m_{\rm p})$ in the scattering kinematics implies that $\mu \sim (m_{\rm dm}/m_{\rm p})$ for $m_{\rm dm} \ll m_{\rm p}$ and $\mu \sim 1$ for $m_{\rm dm} \gg m_{\rm p}$. The proton-DM coupling could also be associated with a long-range interaction that is not mediated by two-particle collisions. We therefore derive a general limit on $\nu_{\rm p-dm}$, independent of the nature of the interaction.

The momentum change of protons as a result of scattering on DM particles over a timescale $1/\nu_{\rm p-dm}$ results in a drag force per unit volume on the plasma: $-(n_{\rm p} m_{\rm p} \nu_{\rm p-dm})\vec{v}_{\rm c}$, where $m_{\rm p}$ and $n_{\rm p}$ are the proton mass and number density. This force generates a longitudinal electric field $\vec{E}$ along the direction of motion, which carries the electrons and protons together at the same bulk velocity $\vec{v}_{\rm c}$ and maintains local quasi-neutrality of the plasma [18],

$$e\vec{E} = m_{\rm e} \nu_{\rm p-dm} \vec{v}_{\rm c}, \tag{1}$$

where m_e is the electron mass.

For a flat rotation curve along the radial coordinate r in cylindrical symmetry, we get $\vec{\nabla} \times \vec{v}_{\rm c} = (1/r)[\partial(r v_{\rm c})/\partial r] = (v_{\rm c}/r)\hat{e}_z$, in the z-direction perpendicular to the disk plane. As in the Biermann Battery case [19], Faraday's Law implies the generation of a vertical magnetic field $\vec{B} = B\hat{e}_z$ at a rate of

$$\frac{\partial \vec{B}}{\partial t} = -c\vec{\nabla} \times \vec{E} = -\left(\frac{c m_{\rm e}}{e}\right) \nu_{\rm p-dm} \left(\frac{v_{\rm c}}{r}\right) \hat{e}_z. \tag{2}$$

Coulomb collisions do not erase a large-scale electric field. They only affect the current driven in the plasma through the relation between the electric field, $\vec{E}$, and conductivity, σ (which is proportional to the electron-proton collision time) through Ohm's law: $\vec{j} = \sigma(\vec{E} + \vec{v} \times \vec{B})$. The resulting limit on the electric current does not limit

---

[*] aloeb@cfa.harvard.edu

the build-up of the magnetic field. In fact, if Faraday's Law was not used to impose a limit on the magnetic field under the quasi-neutrality of the plasma, then the characteristic current, $\vec{j}$, driven by the frictional force on the dark matter would have resulted in a much larger magnetic field based on the other Maxwell equation: $\vec{\nabla} \times \vec{B} - (d\vec{E}/dt) = (4\pi/c)\vec{j}$.

Over the age of the Milky Way disk, $t_{\rm d} \sim 10^{10}$ yr, the magnetic field builds up to a magnitude of

$$B = \left(\frac{cm_{\rm e}}{e}\right)\left(\frac{v_{\rm c}}{r}\right)\nu_{\rm p-dm}t_{\rm d}. \tag{3}$$

The net effect on the plasma originates because of its net bulk motion relative to the dark matter. Collisions occur at an equal rate from all directions if the velocity distribution of the dark matter particles is isotropic and the plasma has no bulk motion relative to the dark matter. But the Milky Way disk has a net rotation relative to the dark matter halo in which it is embedded, generating the above-mentioned magnetic field. The collisions between protons and electrons in the plasma are not associated with a bulk motion of the proton fluid relative to the electron fluid. In fact, quasi-neutrality implies that they move together hydrodynamically. This is achieved through the large-scale electric field in Eq. (1).

Substituting all the above expressions for the fiducial parameters of the Milky Way disk and halo at the Galactocentric radius of the Sun, $r \sim 8$ kpc, yields a magnetic field vertical to the disk plane of magnitude

$$B \sim 2\mu G\left(\frac{\nu_{\rm p-dm}}{0.1\ {\rm s}^{-1}}\right). \tag{4}$$

The measured value of the interstellar magnetic field of a few μG [15,20] places an upper limit on the proton-DM interaction for arbitrary DM particle masses, namely $\nu_{\rm p-dm} \lesssim 0.1\ {\rm s}^{-1}$. We emphasize that the observation of the Galactic field can only set an upper bound on the cross-section because conventional plasma processes were likely responsible for its generation.

Laboratory experiments in superconductors on sub-micron scales with $r \lesssim 10^{-4}$ cm, $v_c \sim c$, $t_{\rm d} \gtrsim 1$ yr and sensitivity to $B \sim 1$ nG could potentially constrain unprecedented levels of $\nu_{\rm p-dm} \lesssim 10^{-24}\ {\rm s}^{-1}$, corresponding to $\sigma \lesssim 10^{-34}\ {\rm cm}^2$ for arbitrarily low DM particle masses, $m_{\rm DM} \ll 1$ GeV. Superconductors are already being incorporated in dark matter searches [21] and the method described here could add a novel concept to existing detection methods. The limits would require exquisite control over noise from interactions with other particles or waves in the environment of the experiment. The optimal design of an experimental set-up based on this novel detection method goes beyond the scope of this paper.

III. CONCLUSIONS

Equations (1)–(3) can be used to limit $\nu_{\rm p-dm}$ for arbitrary DM particle masses and an observed magnetic field in a spinning conductor. The limit also applies to any long-range force between DM and protons.

In deriving this limit we focused on the interaction of protons with DM particles. An analogous limit can be derived by considering any preferential interaction of electrons with DM particles. It is unlikely that the DM particles would produce an identical frictional force density for electrons and ions in a moving conducting medium because of the different masses and couplings of leptons and quarks.

ACKNOWLEDGMENTS

This work was supported in part by grants from the Breakthrough Prize Foundation and by the Black Hole Initiative which is funded by John Templeton Foundation (JTF) and Gordon and Betty Moore Foundation (GBMF).

[1] T. Emken and C. Kouvaris, How blind are underground and surface detectors to strongly interacting dark matter?, Phys. Rev. D **97**, 115047 (2018).

[2] J. L. Feng and J. Kumar, Dark-Matter Particles without Weak-Scale Masses or Weak Interactions, Phys. Rev. Lett. **101**, 231301 (2008).

[3] Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, and J. G. Wacker, Model for Thermal Relic Dark Matter of Strongly Interacting Massive Particles, Phys. Rev. Lett. **115**, 021301 (2015).

[4] E. Kuflik, M. Perelstein, N. R.-L. Lorier, and Y.-D. Tsai, Elastically Decoupling Dark Matter, Phys. Rev. Lett. **116**, 221302 (2016).

[5] S. Knapen, T. Lin, and K. M. Zurek, Light dark matter: Models and constraints, Phys. Rev. D **96**, 115021 (2017).

[6] X. Chen, S. Hannestad, and R. J. Scherrer, Cosmic microwave background and large scale structure limits on the interaction between dark matter and baryons, Phys. Rev. D **65**, 123515 (2002).

[7] C. Dvorkin, K. Blum, and M. Kamionkowski, Constraining dark matter-baryon scattering with linear cosmology, Phys. Rev. D **89**, 023519 (2014).

[8] W. L. Xu, C. Dvorkin, and A. Chael, Probing sub-GeV dark matter-baryon scattering with cosmological observables, Phys. Rev. D **97**, 103530 (2018).

[9] K. K. Boddy and V. Gluscevic, First cosmological constraint on the effective theory of dark matter-proton interactions, Phys. Rev. D **98**, 083510 (2018).

[10] T. R. Slatyer and C.-L. Wu, Early-Universe constraints on dark matter-baryon scattering and their implications for a global 21 cm signal, Phys. Rev. D **98**, 023013 (2018).

[11] E. O. Nadler *et al.* (DES Collaboration), Constraints on Dark Matter Properties from Observations of Milky Way Satellite Galaxies, Phys. Rev. Lett. **126**, 091101 (2021).

[12] K. Maamari, V. Gluscevic, K. K. Boddy, E. O. Nadler, and R. H. Wechsler, Bounds on velocity-dependent dark matter-proton scattering from Milky Way satellite abundance, Astrophys. J. Lett. **907**, L46 (2021).

[13] K. K. Rogers, C. Dvorkin, and H. V. Peiris, New Limits on Light Dark Matter—Proton Cross Section from the Cosmic Large-Scale Structure, Phys. Rev. Lett. **128**, 171301 (2022).

[14] M. J. Reid, K. M. Menten, A. Brunthaler, X. W. Zheng, T. M. Dame, Y. Xu, J. Li, N. Sakai, Y. Wu, K. Immer, B. Zhang, A. Sanna, L. Moscadelli, K. L. J. Rygl, A. Bartkiewicz, B. Hu, L. H. Quiroga-Nuñez, and H. J. van Langevelde, Trigonometric parallaxes of high-mass star-forming regions: Our view of the Milky Way, Astrophys. J. **885**, 131 (2019).

[15] B. T. Draine, *Physics of the Interstellar and Intergalactic Medium* (Princeton University Press, 2011).

[16] L. Spitzer, *Physical Processes in the Interstellar Medium* (Princeton University Press, 1998).

[17] R. Guo, C. Liu, S. Mao, X.-X. Xue, R. J. Long, and L. Zhang, Measuring the local dark matter density with LAMOST DR5 and Gaia DR2, Mon. Not. R. Astron. Soc. **495**, 4828 (2020).

[18] A. Loeb, Electromagnetic characteristics of the dynamics of a self-gravitating quasineutral plasma, Phys. Rev. D **37**, 3484 (1988).

[19] L. Biermann, Über den Ursprung der Magnetfelder auf Sternen und im interstellaren Raum (miteinem Anhang von A. Schlüter), Z. Naturforsch. Teil A **5**, 65 (1950).

[20] A. Ordog, J. C. Brown, R. Kothes, and T. L. Landecker, Three-dimensional structure of the magnetic field in the disk of the Milky Way, Astron. Astrophys. **603**, A15 (2017).

[21] Y.-H. Kim, S.-J. Lee, and B. Yang, Superconducting detectors for rare event searches in experimental astroparticle physics, Supercond. Sci. Technol. **35**, 063001 (2022).