Results on photon-mediated dark matter-nucleus interactions from the PICO-60 C$_3$F$_8$ bubble chamber

B. Ali, I. J. Arnquist, D. Baxter, E. Behnke, M. Bressler, B. Broerman, C. J. Chen, K. Clark, J. I. Collar, P. S. Cooper, C. Cripe, M. Crisler, C. J. Chen, K. Clark, J. I. Collar, P. S. Cooper, C. Cripe, M. Crisler, C. E. Dahl, M. Das, D. Durnford, S. Fallows, J. Farine, R. Filgas, A. García-Viltres, G. Giroux, O. Harris, T. Hillier, E. W. Hoppe, C. M. Jackson, M. Jin, C. B. Krauss, V. Kumar, M. Laurin, I. Lawson, A. Leblanc, H. Leng, I. Levine, C. Licciardi, S. Linden, P. Mitra, V. Monette, C. Moore, R. Neilson, A. J. Noble, H. Nozard, S. Pal, M.-C. Piro, A. Plante, S. Priya, C. Rethmeier, A. E. Robinson, J. Savoie, A. Somnenschein, N. Starinski, I. Štekl, D. Tiwari, E. Vázquez-Jáuregui, U. Wichoski, V. Zacek, and J. Zhang (PICO Collaboration)

Institute of Experimental and Applied Physics, Czech Technical University in Prague, Prague, Cz-12800, Czech Republic
Pacific Northwest National Laboratory, Richland, Washington 99354, USA
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
Department of Physics, Indiana University South Bend, South Bend, Indiana 46634, USA
Department of Physics, Drexel University, Philadelphia, Pennsylvania 19104, USA
Department of Physics, Queen’s University, Kingston, K7L 3N6, Canada
Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA
Enrico Fermi Institute, KICP, and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA
High Energy Nuclear & Particle Physics Division, Saha Institute of Nuclear Physics, Kolkata, India
Department of Physics, University of Alberta, Edmonton, T6G 2E1, Canada
School of Biological, Chemical, and Forensic Sciences, Laurentian University, Sudbury, ON P3E 2C6, Canada
SNOLAB, Lively, Ontario, P3Y 1N2, Canada
Department of Physics, Carleton University, Ottawa, Ontario, K1S 5B6, Canada
Instituto de Física, Universidad Nacional Autónoma de México, México D. F. 01000, México
Northeastern Illinois University, Chicago, Illinois 60625, USA
Département de Physique, Université de Montréal, Montréal, H3C 3J7, Canada
Materials Research Institute, Penn State, University Park, Pennsylvania 16802, USA

(Dated: April 25, 2022)

Many compelling models predict dark matter coupling to the electromagnetic current through higher multipole interactions, while remaining electrically neutral. Different multipole couplings have been studied, among them anapole moment, electric and magnetic dipole moments, and millicharge. This study sets limits on the couplings for these photon-mediated interactions using non-relativistic contact operators in an effective field theory framework. Using data from the PICO-60 bubble chamber leading limits for dark matter masses between 2.7 GeV/c$^2$ and 24 GeV/c$^2$ are reported for the coupling of these photon-mediated dark matter-nucleus interactions. The detector was filled with 52 kg of C$_3$F$_8$ operating at thermodynamic thresholds of 2.45 keV and 3.29 keV, reaching exposures of 1404 kg-day and 1167 kg-day, respectively.

INTRODUCTION

The identification of dark matter (DM), one of the main questions in contemporary physics, remains an elusive problem [1–7]. Direct detection experiments are low background detectors that aim to detect tiny energy deposits, O(1-100)-keV, produced by the elastic collision of Weakly Interacting Massive Particles (WIMP) [8–11].
WIMPs remain promising DM candidates [12–14], with several experiments setting tight constraints with cross-sections of the order of $10^{-45}$ cm$^2$ [15–24] for masses at approximately 100 GeV/c$^2$. Historically, results have been reported for couplings in terms of spin-independent (SI) and spin-dependent (SD) cross-sections [25, 26]. As increasingly sensitive searches fail to observe convincing candidate events, interest in other interactions of DM with baryonic matter surge, well motivated by different physics scenarios. DM is electrically neutral, but coupling to the photon through higher multipole interactions is possible [11, 27–37]. Many couplings have been studied, such as anapole moment [37–41], magnetic [30, 37, 42–44] and electric [30, 44] dipole moments, and with a millicharge [45–50]. These photon-mediated interactions could be relevant for low WIMP masses, O(1–10)-GeV/c$^2$ [51]. This work considers operators within an effective field theory as a benchmark scenario to establish limits on photon-mediated couplings using data from the PICO-60 bubble chamber.

**PICO-60 EXPERIMENT**

The PICO-60 bubble chamber was operated two km deep underground at SNOLAB [52] between November 2016 and January 2017 for a first physics run and from April to June 2017 for a second run. The detector consisted of a fused silica inner vessel filled with $(52.2 \pm 0.5)$ kg of C$_2$F$_8$ in a superheated state. The inner vessel was immersed in a stainless steel pressure vessel filled with mineral oil, acting as a thermal bath and hydraulic fluid. The chamber had four cameras installed to photograph the bubble nucleation process and eight piezoelectric acoustic transducers were attached to the inner vessel to record the acoustic emissions from bubble nucleations. The first physics run had an exposure of 1167 kg-day at a 3.29-keV thermodynamic Seitz threshold, while the second had an exposure of 1404 kg-day at a 2.45-keV Seitz threshold. These two searches established lead limits on direct detection experiments since it considers the non-relativistic quantum mechanical operators contributing to the elastic scattering of DM with a nucleus. These interactions could provide different nuclear responses compared to the SI and SD scenarios. In this work, higher multipole interactions are studied, such as anapole moment, magnetic and electric dipole moments, and millicharge. These interactions can be generically parameterized in terms of non-relativistic effective operators [57–60], for which the nuclear scattering cross-sections depend on exchanged momentum, relative velocity, and nucleon and DM spins. The relevant contact operators involved in the interactions reported in this work are.

**NON-RELATIVISTIC EFFECTIVE FIELD THEORY**

A non-relativistic effective field theory (NREFT) approach is suitable to extend the standard SI and SD searches. This framework allows generalizing the analysis of direct detection experiments since it considers the non-relativistic quantum mechanical operators contributing to the elastic scattering of DM with a nucleus. These interactions could provide different nuclear responses compared to the SI and SD scenarios. In this work, higher multipole interactions are studied, such as anapole moment, magnetic and electric dipole moments, and millicharge. These interactions can be generically parameterized in terms of non-relativistic effective operators [57–60], for which the nuclear scattering cross-sections depend on exchanged momentum, relative velocity, and nucleon and DM spins. The relevant contact operators involved in the interactions reported in this work are.
the unique feature that it interacts only with external electromagnetic currents $J_\mu = \partial^\nu F_{\mu \nu}$ [64]. In the non-relativistic limit, the effective operator for anapole interactions, $O_A$, is a linear combination of the momentum-independent operator $O_8$ and the momentum-dependent $O_9$:

$$O_A = c_A \sum_{N=n,p} (Q_N O_8 + g_N O_9) ,$$

where $Q_N$ is the nucleon charge ($Q_p = e$, $Q_n = 0$) while $g_N$ is the nucleon g-factor ($g_p = 5.59$ and $g_n = -3.83$). This interaction is expressed as $O_A = c_A [eO_8 + (g_p + g_n)O_9]$ for CsF$_8$. Fig. 2 (upper left) shows the coupling for DM interacting through the anapole moment. The 90% C.L. limits on the coupling from the profile likelihood analysis of the PICO-60 CsF$_8$ combined blind exposure is shown and compared to results from the XENON-1T [65] and DEAP-3600 experiments [66]. XENON-1T and DEAP-3600 are leading experiments for SI interactions with noble liquids, using xenon and argon, respectively. PICO-60 is the leading experiment for SD interactions, using a fluorine target.

### Dark matter with magnetic dipole moment

Contact interactions ($|q| \ll m_\phi$), where $m_\phi$ is the mass of the mediator, are independent of the exchanged momentum; however, long-range interactions ($|q| \gg m_\phi$) are enhanced at small momentum transfer. Examples of long-range interactions are DM with electric or magnetic dipole moments and millicharged DM. These arise from the exchange of a massless mediator, where the propagator term enhances the interaction. Considering the DM particle as a Dirac fermion acquiring a magnetic dipole moment, the effective interaction is given by:

$$L_{MD} = \frac{\mu_\chi}{2} \bar{\chi} \sigma^{\mu\nu} \chi F_{\mu \nu} ,$$

where the spinor $\chi$ represents the Dirac DM particle, $\mu_\chi$ is the magnetic moment coupling, and $\sigma^{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu]$. Similar to the anapole moment scenario, the non-relativistic shape of the effective operator for magnetic dipole interactions, $O_{MD}$, can be expressed in terms of contact operators in the NREFT. $O_{MD}$ depends on the operators $O_1$, $O_4$, $O_5$, and $O_6$ and is expressed as follows:

$$O_{MD} = 2e\mu_\chi \sum_{N=n,p} \left[ Q_N m_N O_1 + 4Q_N \frac{m_\chi m_N}{q^2} O_5 \right. + 2g_N m_\chi (O_4 - \frac{1}{q^2} O_6) \left. \right] .$$

where $m_N$ is the nucleon mass, $\vec{q}$ is the exchanged momentum, $\vec{v}_\perp$ is the perpendicular component of the velocity to the momentum transfer, $\vec{S}$ is the spin of the DM particle, and $\vec{S}'$ is the spin of the nucleon. The numbering scheme is followed from the NREFT definition of the operators, a result of an index in the general Lagrangian [58].

Photon-mediated interactions were studied using the WIMPy_NREFT software developed by Kavanagh et al. [61] which allows for the calculation of dark matter nucleus scattering rates in the framework of a non-relativistic effective field theory [57, 58]. The rate calculations for the operators involved in the interactions are in agreement with results from the dmdd (dark matter direct detection) software developed by Gluscevic et al. [62, 63]. The scattering rates for the operators $O_1, O_4, O_5, O_6, O_8, O_9,$ and $O_{11}$, involved in the photon-mediated interactions, were evaluated for both software packages. Fig. 1 shows the rates for the photon-mediated interactions, obtained with WIMPy_NREFT for a 5 GeV/c$^2$ DM particle. The scattering rate in fluorine for the anapole moment is significantly higher than in xenon or argon. This is primarily due to the operator $O_9$ being a function of nuclear spin. In addition, the factor $\vec{q}/m_N$, relevant for operators $O_5, O_6, O_9,$ and $O_{11}$, results in enhanced couplings for low nuclear masses such as fluorine for WIMP masses below 20 GeV/c$^2$.

### Dark matter with anapole moment

The anapole moment is the lowest electromagnetic moment allowed for a Majorana particle. It is generated by a toroidal electric current which confines the magnetic field within a torus. It is equivalent to having a particle with a toroidal dipole moment. If the DM particle is assumed to be a Majorana fermion scattering off a nucleus via a spin-1 mediator that kinetically mixes with the photon, then the effective interaction is:

$$L_A = c_A \bar{\chi} \gamma^\mu \gamma^5 \chi \partial^\nu \mathcal{F}_{\mu \nu} ,$$

where the $\chi$ spinor represents the Majorana DM particle, $c_A$ the anapole moment coupling strength and $\mathcal{F}_{\mu \nu}$ the electromagnetic field tensor. The anapole moment has the unique feature that it interacts only with external
Fig. 1: Scattering rates in $\text{C}_3\text{F}_8$ (red), xenon (dashed blue), and argon (dotted green) for a DM particle with mass of 5 GeV/c$^2$ with coupling through the anapole moment (upper left, for a coupling of $3.6 \times 10^{-8}$ GeV$^{-2}$), millicharge (upper right, for a coupling of $2.2 \times 10^{-8}$ e), magnetic dipole moment (lower left, for a coupling of $2.8 \times 10^{-8}$ GeV$^{-1}$), and electric dipole moment (lower right, for a coupling of $2.8 \times 10^{-8}$ GeV$^{-1}$). The rates were obtained with the WIMpy\_NREFT package [61].

Fig. 2 (lower left) presents the 90% C.L. limits on the coupling for DM interacting through the magnetic dipole moment.

**Dark matter with electric dipole moment**

Likewise, assuming a Dirac fermion as the DM particle acquiring an electric dipole moment, the effective Lagrangian for the coupling can be written as:

$$\mathcal{L}_{\text{ED}} = \frac{d_\chi}{2} i \bar{\chi} \sigma^{\mu\nu} \gamma^5 \chi F_{\mu\nu},$$

where $d_\chi$ is the electric dipole moment coupling. A DM particle with a permanent electric dipole moment must have a non-zero spin, and $d_\chi$ satisfies time-reversal and parity violation [30]. The non-relativistic operator participating in this interaction, $\mathcal{O}_{\text{ED}}$, is a function of the $\mathcal{O}_{11}$ operator. It is expressed as:

$$\mathcal{O}_{\text{ED}} = 2 ed_\chi \frac{1}{q^2} \mathcal{O}_{11}. \quad (6)$$

Fig. 2 (lower right) shows the coupling for DM interacting through the electric dipole moment (90% C.L. limits).

**Dark matter with millicharge**

Millicharged particles have attracted interest since they represent elegant extensions to the Standard Model...
FIG. 2: Exclusion limits at 90% C.L. for the anapole moment (upper left), millicharge (upper right), magnetic dipole moment (lower left), and electric dipole moment (lower right) couplings. The limits are derived from the profile likelihood analysis of the PICO-60 C₃F₈ (red) combined blind exposure. Limits from XENON-1T (dashed blue) [65] and DEAP-3600 (dotted green) [66] using xenon and argon, respectively, are also shown.

[67–69]. A millicharged DM particle would carry a fraction of the electron charge and many searches have been performed [65, 70–78]. Considering a Dirac fermion, the interaction Lagrangian of the millicharged DM is given by:

$$\mathcal{L}_M = e \epsilon_\chi A_\mu \bar{\chi} \gamma^\mu \chi,$$

where $A_\mu$ is the SM photon and $\epsilon_\chi$ is the millicharge (a fraction of the electron charge $e$). The non-relativistic millicharge operator, $\mathcal{O}_M$, is only a function of the $\mathcal{O}_1$ operator but with a $q^2$ dependence:

$$\mathcal{O}_M = e^2 \epsilon_\chi \frac{1}{q^2} \mathcal{O}_1.$$

Conclusions

The results presented in this work show the excellent physics reach of the bubble chamber technology using fluorine targets. World-leading limits for the coupling of photon-mediated DM interactions for masses from 2.7 GeV/$c^2$ and up to 24 GeV/$c^2$ are reported. The analysis was performed using a non-relativistic effective field theory to determine the coupling strength of the effective contact interaction operators. Assuming DM is a fermion with electromagnetic moments, the lowest order electromagnetic interaction is through the magnetic or electric dipole moments. Analysis from the PICO-60 bubble chamber sets leading limits for these couplings, as low as $2.1 \times 10^{-9}$ GeV$^{-1}$ for masses between 2.7 GeV/$c^2$
and 11.7 GeV/c^2 (electric) and 5.8 × 10^{-9} GeV^{-1} between 3 GeV/c^2 and 9.5 GeV/c^2 (magnetic). Furthermore, the only possible electromagnetic moment for a Majorana fermion is the anapole moment since the magnetic and electric dipole moments vanish. The PICO-60 experiment sets leading limits for masses between 2.7 GeV/c^2 and 24 GeV/c^2 and above 265 GeV/c^2 with couplings as low as 1.4 × 10^{-5} GeV^{-2}. Lastly, millicharged particles are theoretically well-motivated to account for a fraction of the DM. Leading couplings as low as 2.1 × 10^{-16}c for masses between 2.7 GeV/c^2 and 12 GeV/c^2 are obtained with data from the PICO-60 detector. The couplings reported are the strongest limits set for photon-mediated DM interactions in the low mass WIMP range (2.7-24 GeV/c^2).

**ACKNOWLEDGEMENTS**

The PICO collaboration wishes to thank SNOLAB and its staff for support through underground space, logistical and technical services. SNOLAB operations are supported by the Canada Foundation for Innovation and the Province of Ontario Ministry of Research and Innovation, with underground access provided by Vale at the Creighton mine site. We wish to acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canada Foundation for Innovation (CFI) for funding, and the Arthur B. McDonald Canadian Astroparticle Physics Research Institute. We acknowledge that this work is supported by the National Science Foundation (NSF) (Grant 0919526, 1506337, 1242637, and 1205987), by the U.S. Department of Energy (DOE) Office of Science, Office of High Energy Physics (grants No. DE-SC0017815 and DE-SC-0012161), by the DOE Office of Science Graduate Student Research (SCGSR) Contract No.DE-AC02-07CH11359, and from Pacific Northwest National Laboratory, which is operated by Battelle for the U.S. Department of Energy under Contract No. DE-AC05-76RL01830. We also thank Compute Canada (www.computecanada.ca) and the Centre for Advanced Computing, ACENET, Calcul Québec, Compute Ontario, and WestGrid for computational support. The work of M. Bressler is supported by the Department of Energy Office of Science Graduate Instrumentation Research Award (GIRA). The work of D. Durnford is supported by the NSERC Canada Graduate Scholarships - Doctoral program (CGSD). IUSB wishes to acknowledge the work of D. Marizata.

* Corresponding: agarciaviltres@gmail.com
† Corresponding: ericvj@fisica.unam.mx
‡ now at Argonne National Laboratory

[1] P. A. Zyla et al. (Particle Data Group), PTEP 2020, 083C01 (2020).
[2] E. Komatsu, J. Dunkley, M. R. Nolta, C. L. Bennett, B. Gold, G. Hinshaw, N. Jarosik, D. Larson, M. Limon, L. Page, D. N. Spergel, M. Halpern, R. S. Hill, A. Kogut, S. S. Meyer, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright, The Astrophysical Journal Supplement Series 180, 330 (2009).
[3] G. Jungman, M. Kamionkowski, and K. Griest, Physics Reports 267, 195 (1996).
[4] M. W. Goodman and E. Witten, Phys. Rev. D 31, 3059 (1985).
[5] P. Cushman et al., (2013).
[6] M. I. Gresham and K. M. Zurek, Phys. Rev. D 89, 123521 (2014).
[7] E. D. Nobile, G. B. Gelmini, and S. J. Witte, Journal of Cosmology and Astroparticle Physics 2016, 009 (2016).
[8] G. B. Gelmini, Reports on Progress in Physics 80, 082201 (2017).
[9] V. Berezinsky, A. Bottino, J. Ellis, N. Fornengo, G. Mignola, and S. Scopel, Astroparticle Physics 5, 1 (1996).
[10] G. Servant and T. M. Tait, Nuclear Physics B 650, 391 (2003).
[11] M. Pospelov and T. ter Veldhuis, Physics Letters B 480, 181 (2000).
[12] L. Roszkowski, E. M. Sessolo, and S. Trojanowski, Reports on Progress in Physics 81, 066201 (2018).
[13] G. Bertone, N. Bozorgnia, J. Kim, S. Liem, C. McCabe, S. Otten, and R. Austri, Journal of Cosmology and Astroparticle Physics 2018 (2017), 10.1088/1475-7516/2018/03/026.
[14] J. Billard, M. Boulay, S. Cebrian, L. Covi, G. Fiorillo, A. M. Green, J. Kopp, B. Majorovits, K. Palladino, F. Petricca, L. Roszkowski, and M. Schumann, Reports
[70] O. Moreno et al. (LDMX Collaboration), in APS April Meeting Abstracts, APS Meeting Abstracts (2019) p. T04.003.
[71] J. M. Cline, Z. Liu, and W. Xue, Phys. Rev. D 85, 101302 (2012).
[72] D. Budker, P. W. Graham, H. Ramani, F. Schmidt-Kaler, C. Smorra, and S. Ulmer, PRX Quantum 3, 010330 (2022).
[73] G. Magill, R. Plestid, M. Pospelov, and Y.-D. Tsai, Physical Review Letters 122 (2019), 10.1103/PhysRevLett.122.071801.
[74] K. J. Kelly and Y.-D. Tsai, Phys. Rev. D 100, 015043 (2019).
[75] R. Plestid, V. Takhistov, Y.-D. Tsai, T. Bringmann, A. Kusenko, and M. Pospelov, Physical Review D 102 (2020), 10.1103/PhysRevD.102.115032.
[76] H. Liu, N. Outmezguine, D. Redigolo, and T. Volansky, Physical Review D 100 (2019), 10.1103/PhysRevD.100.123011.
[77] A. Haas, C. S. Hill, E. Izaguirre, and I. Yavin, Physics Letters B 746, 117 (2015).
[78] G. Magill, R. Plestid, M. Pospelov, and Y.-D. Tsai, Phys. Rev. Lett. 122, 071801 (2019).