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Results on photon-mediated dark matter-nucleus interactions from the PICO-60 C_3F_8 bubble chamber

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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 and 24 GeV/c^2 and above 265 GeV/c^2 (anapole moment), 2.7 and 11.7 GeV/c^2 (electric moment), 3 and 9.5 GeV/c^2 (magnetic moment), and 2.7 and 12 GeV/c^2 (millicharged) are reported for the coupling of these photon-mediated dark matter-nucleus interactions. The detector was filled with 52 kg of C_3F_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 de-

posits, 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, 52]. 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.

PIC0-60 EXPERIMENT

The PICO-60 bubble chamber was operated two km deep underground at SNOLAB [53] 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_3F_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 leading limits on SD couplings, setting the most stringent direct-detection constraints to date on the WIMP-proton spin-dependent cross-section at 2.5×10^{-41} cm^2 for a 25 GeV/c^2 WIMP. The analysis reported in this manuscript uses the same data with a different approach and interpretation. Details of the experimental setup, data analysis, background estimates, and WIMP search results are found in Refs. [23, 24]. The limit calculation method for SD and SI couplings, previously published [24] by the PICO collaboration, is followed in this work. Namely, the exclusion limits for the combined datasets are determined with a Profile Likelihood Ratio (PLR) test [54]. Efficiency functions are obtained from calibration data using the emcee [55] Markov Chain Monte Carlo (MCMC) python code package [56]. These functions are used to obtain the WIMP detection efficiency, for each of the couplings (expressed as functions of effective operators for the photon-mediated interactions), by integration over the nuclear recoil spectrum from an astrophysical WIMP flux for an array of potential WIMP masses. The result is a tensor containing the WIMP detection efficiency, dependent on the interaction, for each thermodynamic threshold and WIMP mass. A likelihood surface is created from this tensor at 2.45 and 3.29 keV, which is a function of the WIMP detection efficiency. This surface is convolved with a two-dimensional Gaussian function that accounts for the uncertainty of the thermodynamic thresholds. Next, the maximum of the likelihood surface for each WIMP mass is determined and used to calculate the optimal coupling. The ratio of the likelihood for a particular coupling to the maximum likelihood over all couplings is used to construct a test statistic. The exclusion curve for each of the couplings reported is obtained with toy datasets generating points in a grid of WIMP masses and couplings. A point is excluded if the evaluated PLR test statistic is larger than 90% of toy dataset test statistics. The exclusion limits consider a local dark matter density $\rho_D = 0.3$ GeV/c^2/cm^3 within the standard halo parametrization [57]. The same astrophysical parameters as in the SD and SI analysis were assumed.

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 [58–61], for which the nuclear scattering cross-sections depend on exchanged momentum, relative velocity, and nucleon and DM spins. The relevant contact operators in-

volved in the interactions reported in this work are,

$$\mathcal{O}_1 = 1_\chi 1_N \qquad \mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right) \qquad \mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp \qquad \mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

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, $\vec{S}_\chi$ is the spin of the DM particle, and $\vec{S}_N$ 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 [59].

Photon-mediated interactions were studied using the `WIMpy_NREFT` software developed by Kavanagh et al. [62] which allows for the calculation of dark matter nucleus scattering rates in the framework of a non-relativistic effective field theory [58, 59]. 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. [63, 64]. The scattering rates for the operators $\mathcal{O}_1, \mathcal{O}_4, \mathcal{O}_5, \mathcal{O}_6, \mathcal{O}_8, \mathcal{O}_9$, and $\mathcal{O}_{11}$, 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 $\mathcal{O}_9$ being a function of nuclear spin. In addition, the factor $\vec{q}/m_N$, relevant for operators $\mathcal{O}_5, \mathcal{O}_6, \mathcal{O}_9$, and $\mathcal{O}_{11}$, 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:

$$\mathcal{L}_\mathcal{A} = c_\mathcal{A} \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} \ , \tag{1}$$

where the χ spinor represents the Majorana DM particle, $c_\mathcal{A}$ the anapole moment coupling strength and $F_{\mu\nu}$ the electromagnetic field tensor. The anapole moment has the unique feature that it interacts only with external electromagnetic currents $\mathcal{J}_\mu = \partial^\nu F_{\mu\nu}$ [65]. In the non-relativistic limit, the effective operator for anapole interactions, $\mathcal{O}_\mathcal{A}$, is a linear combination of the momentum-independent operator $\mathcal{O}_8$ and the momentum-dependent $\mathcal{O}_9$:

$$\mathcal{O}_\mathcal{A} = c_\mathcal{A} \sum_{N=n,p} \left(\mathcal{Q}_N \mathcal{O}_8 + g_N \mathcal{O}_9\right) \ , \tag{2}$$

where $\mathcal{Q}_N$ is the nucleon charge ($\mathcal{Q}_p = e$, $\mathcal{Q}_n = 0$) while g_N is the nucleon g-factor ($g_p = 5.59$ and $g_n = -3.83$). This interaction is expressed as $\mathcal{O}_\mathcal{A} = c_\mathcal{A}[e\mathcal{O}_8 + (g_p + g_n)\mathcal{O}_9]$ for C_3F_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 C_3F_8 combined blind exposure is shown and compared to results from the XENON-1T [66] and DEAP-3600 experiments [67]. 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 ($|\vec{q}| \ll m_\phi$), where m_ϕ is the mass of the mediator, are independent of the exchanged momentum; however, long-range interactions ($|\vec{q}| \gg m_\phi$) 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:

$$\mathcal{L}_{\mathcal{MD}} = \frac{\mu_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} \ , \tag{3}$$

where the spinor χ represents the Dirac DM particle, μ_χ 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, $\mathcal{O}_{\mathcal{MD}}$, can be expressed in terms of contact operators in the NREFT. $\mathcal{O}_{\mathcal{MD}}$ depends on the operators $\mathcal{O}_1$, $\mathcal{O}_4$, $\mathcal{O}_5$, and $\mathcal{O}_6$ and is expressed as follows:

$$\mathcal{O}_{\mathcal{MD}} = 2e\mu_\chi \sum_{N=n,p} \Bigg[\mathcal{Q}_N m_N \mathcal{O}_1 + 4\mathcal{Q}_N \frac{m_\chi m_N}{q^2}\mathcal{O}_5 + 2g_N m_\chi (\mathcal{O}_4 - \frac{1}{q^2}\mathcal{O}_6)\Bigg] \ . \tag{4}$$

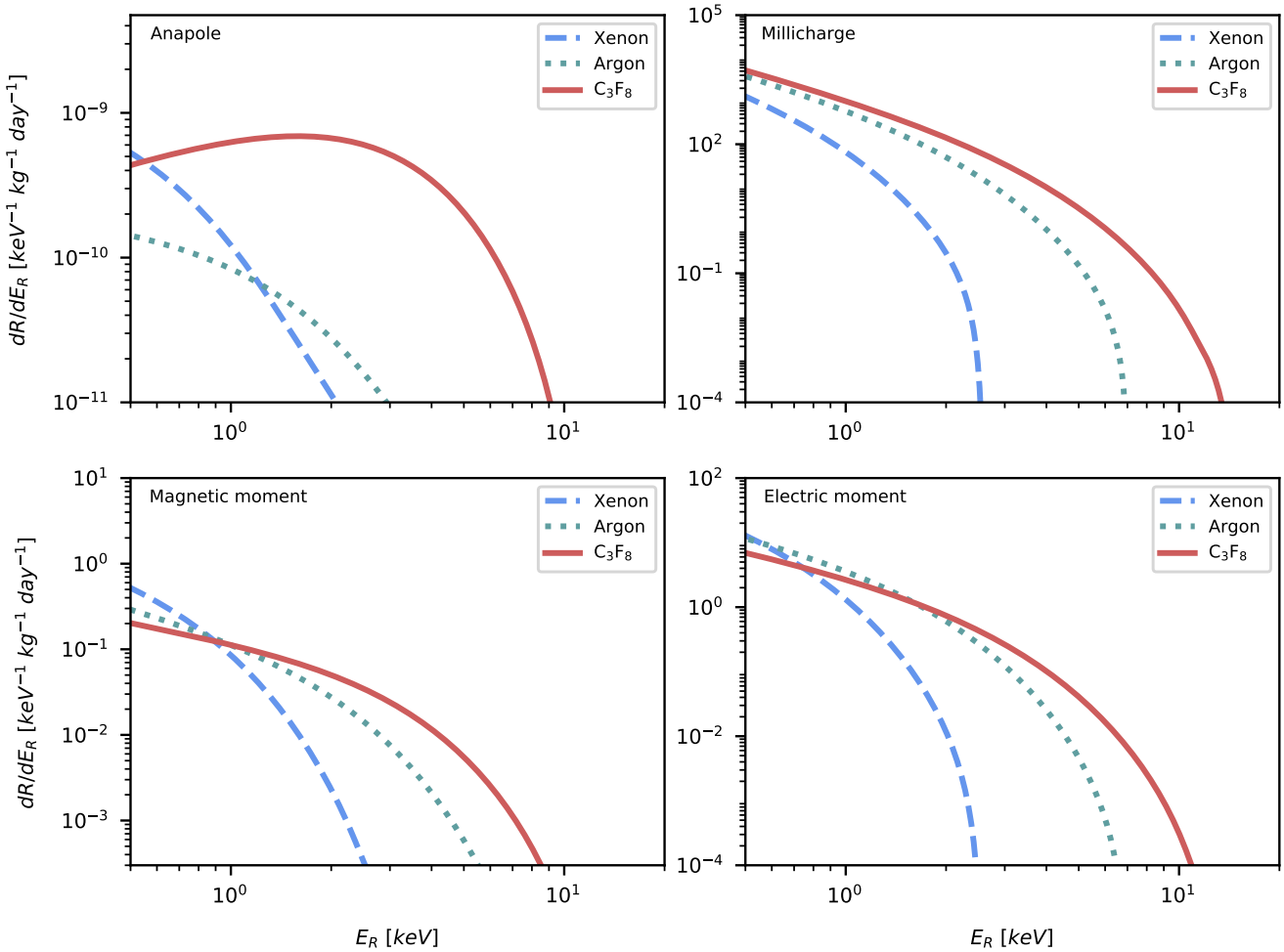

FIG. 1: Scattering rates in C_3F_8 (red), xenon (dashed blue), and argon (dotted green) for a DM particle with mass of 5 GeV/c^2 with coupling through the anapole moment (upper left, for a coupling of 3.6×10^{-8} GeV^{-2}), millicharge (upper right, for a coupling of $2.2 \times 10^{-8}\, e$), magnetic dipole moment (lower left, for a coupling of 2.8×10^{-8} GeV^{-1}), and electric dipole moment (lower right, for a coupling of 2.8×10^{-8} GeV^{-1}). The rates were obtained with the `WIMpy_NREFT` package [62].

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:

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

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

$$\mathcal{O}_{\mathcal{ED}} = 2ed_\chi \frac{1}{q^2}\mathcal{O}_{11}. \tag{6}$$

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

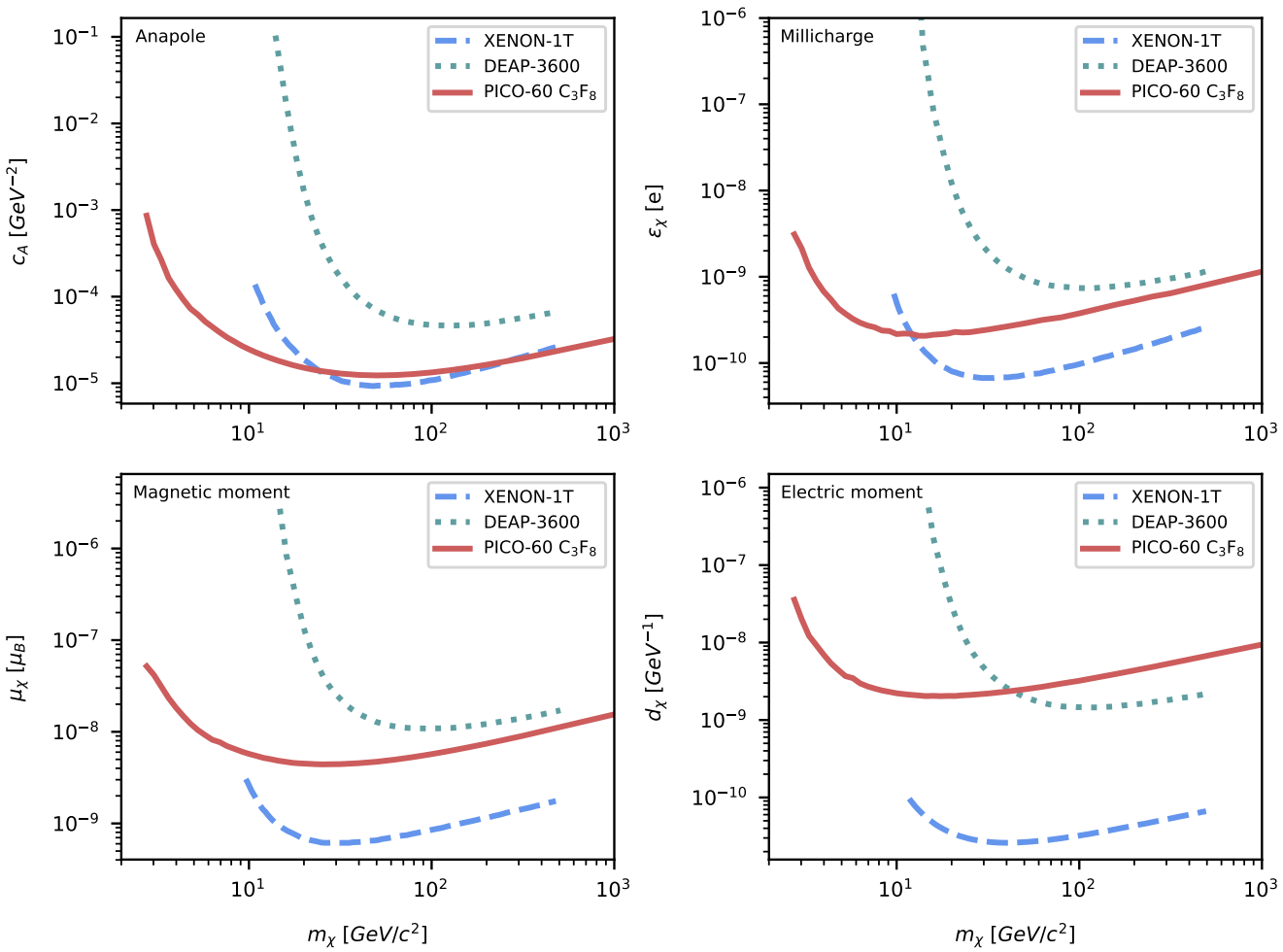

FIG. 2: Exclusion limits at 90% C.L. for the anapole moment (upper left), millicharge (upper right), magnetic dipole moment (lower left), and electric dipole moment (lower right) couplings. The limits are derived from the profile likelihood analysis of the PICO-60 C_3F_8 (red) combined blind exposure. Limits from XENON-1T (dashed blue) [66] and DEAP-3600 (dotted green) [67] using xenon and argon, respectively, are also shown.

[68–70]. A millicharged DM particle would carry a fraction of the electron charge and many searches have been performed [66, 71–79]. Considering a Dirac fermion, the interaction Lagrangian of the millicharged DM is given by:

$$\mathcal{L}_{\mathcal{M}} = e\epsilon_\chi A_\mu \bar{\chi}\gamma^\mu \chi, \tag{7}$$

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

$$\mathcal{O}_{\mathcal{M}} = e^2\epsilon_\chi \frac{1}{q^2}\mathcal{O}_1. \tag{8}$$

Fig. 2 (upper right) presents the 90% C.L. limits on the coupling for millicharged DM.

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 2.1×10^{-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 $2.1 \times 10^{-10}e$ 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). The future program of the PICO collaboration includes PICO-40L and PICO-500, bubble chambers with target masses of 40 and 250 liters, respectively. These detectors will explore lower couplings for photon-mediated interactions by testing different scenarios such as technicolor, composite dark sector, supersymmetry, and simplified leptophilic and light dark sectors.

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