Photon-mediated dark-matter-nucleus interactions in the PICO-60 C_3F_8 bubble chamber

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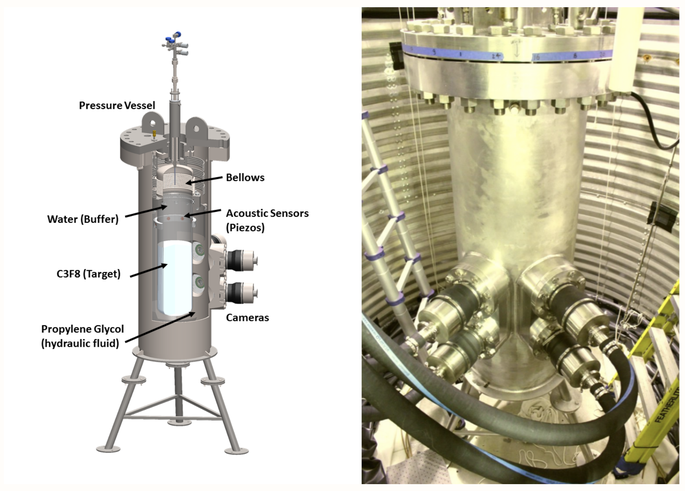
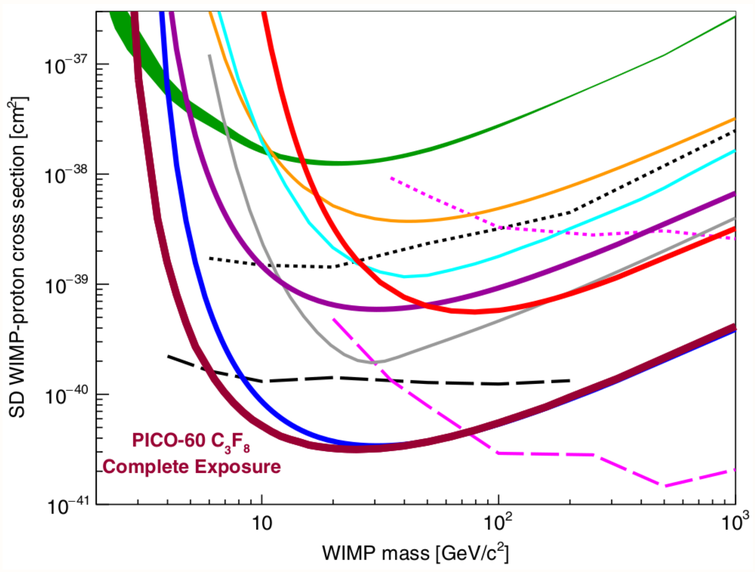
Introduction

- Understanding the nature of DM remains an elusive problem.
- Many couplings have been studied, such as the anapolar moment, magnetic and electric dipole moments, and with a millicharge.
- DM is electrically neutral, but coupling with the photon through higher multipole interactions is possible.



Left: A schematic representation of the PICO-60 bubble chamber. Right: PICO-60 detector inside water tank at SNOLAB.

- The PICO-60 bubble chamber was operated at 2 km depth at SNOLAB monitored by 4 cameras and piezoelectric sensors.
- It was operated between November 2016 and January 2017 in its first physical run and from April to June 2017 in a second run.
- The detector consisted of a fused silica inner vessel filled with (52.2 ± 0.5) kg of C_3F_8 in a superheated state.

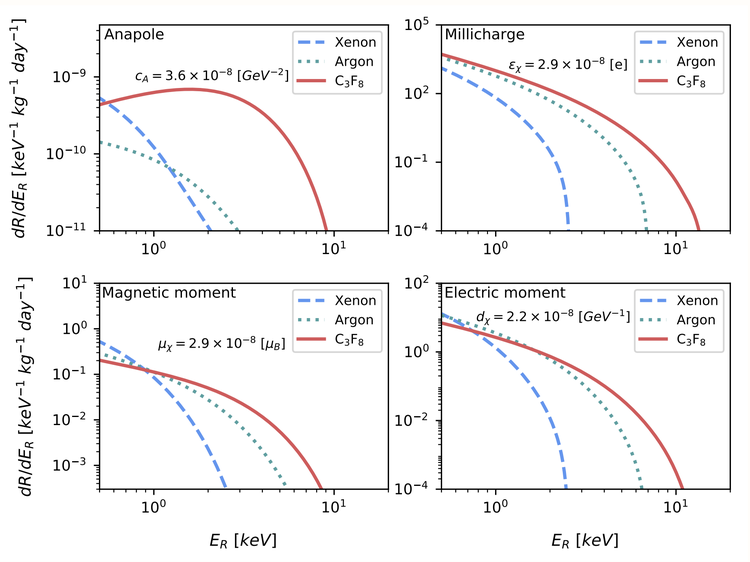


The 90% C.L. limit on the SD WIMP-proton cross section from the profile likelihood analysis of the PICO-60 C_3F_8 complete exposure.

- Both searches with this chamber established the main limits of the SD couplings (2.5×10^{-41} cm^2 for a 25 GeV/c^2 WIMP).
- We consider a NREFT to establish the limits of photon-mediated couplings using data from the PICO-60 bubble chamber.

Non-relativistic effective field theory

- A NREFT approach is useful to diversify classical SI/SD searches.
- Higher multipole interactions such as anapolar momentum, magnetic and electric dipole moments, and millicharge are discussed.



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

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- Interactions were studied using the `WIMpy_NREFT` software developed by Kavanagh .
- The scattering rate in fluorine for the anapole moment is significantly higher than in xenon or argon.

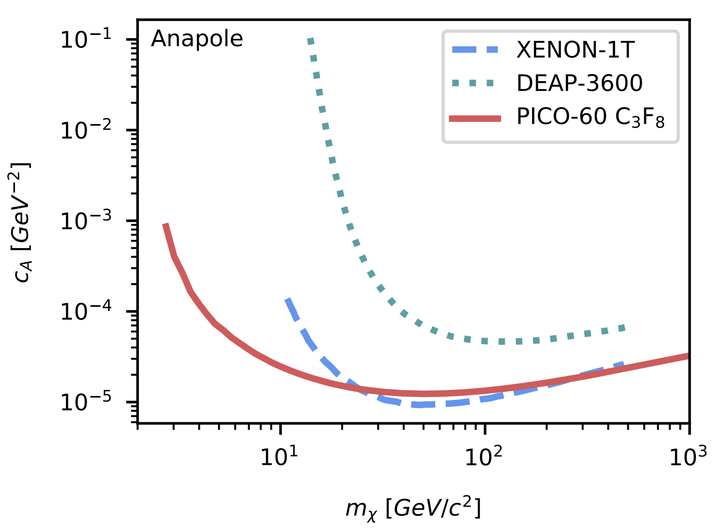
Dark matter with anapole moment

- The anapolar momentum is the smallest electromagnetic momentum allowed for a Majorana particle.
- If we assume that the DM particle scattering through a spin 1 mediator and this is kinetically mixed with the photon:

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

- Effective operator for anapole interactions:

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

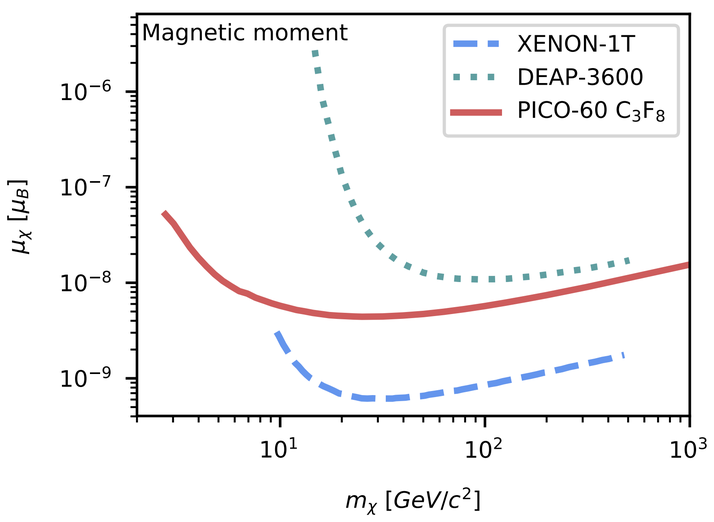


Exclusion limits at 90% C.L. for the anapole moment coupling.

Dark matter with magnetic dipole moment

- The interaction of DM with electric or magnetic dipole moment and millicharged DM are examples of long-range interactions.
- The effective interaction lagrangian is given by:

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



Exclusion limits at 90% C.L. for the magnetic dipole coupling .

- Effective operator for magnetic dipole interactions:

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

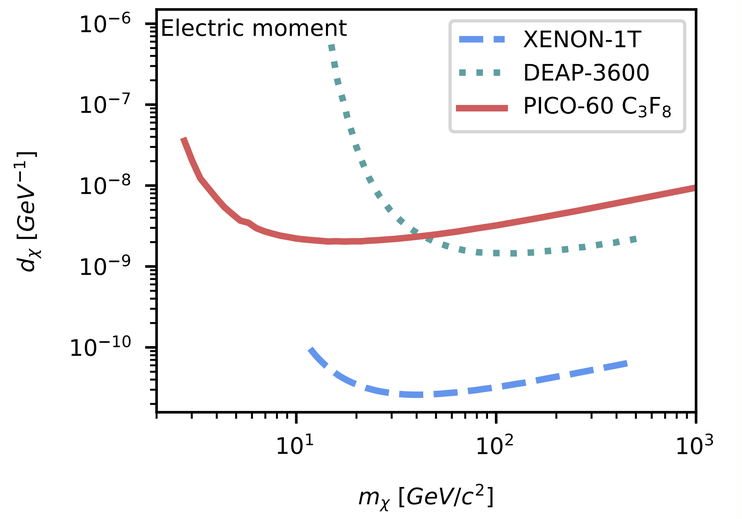
Dark matter with electric dipole moment

- Assuming a Dirac fermion as the DM particle that acquires an electric dipole moment, the effective Lagrangian is

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

- The non-relativistic operator participating in this interaction is expressed as:

$$\mathcal{O}_{\mathcal{ED}} = 2e d_\chi \frac{1}{q^2} \mathcal{O}_{11}.$$



Exclusion limits at 90% C.L. for the electric dipole coupling.

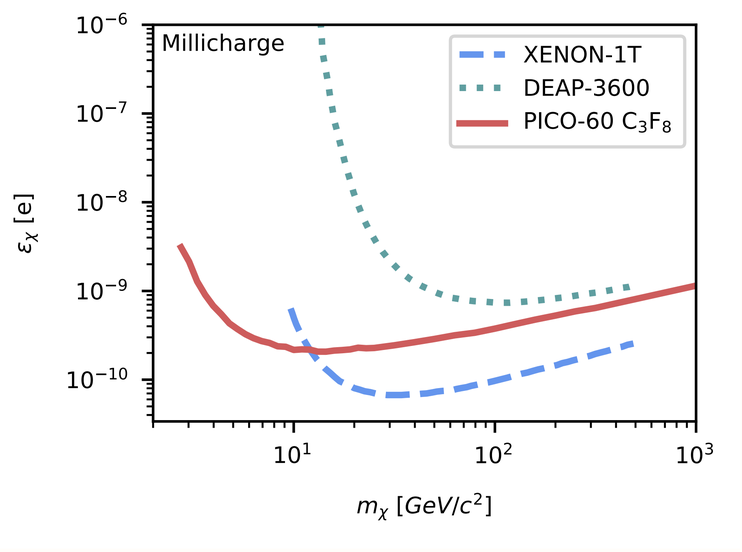
Dark matter with millicharge

- Millicharged particles represent elegant extensions to the SM.
- Interaction Lagrangian of the millicharged DM is given by:

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

- Non-relativistic millicharge operator:

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



Exclusion limits at 90% C.L. for the millicharge coupling.

Conclusions

- Results presented show the excellent physical range of bubble chambers using fluorine targets.
- Leading limits have been reported for masses from 2.7-24 GeV/c^2.
- For DM being a fermion with electromagnetic moments, the lowest order electromagnetic interaction is 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).
- For a Majorana fermion the only possible electromagnetic moment is the anapole moment, PICO-60 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}
- For millicharged DM particles 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

References

[1] P. A. Zyla *et al.*, "Review of Particle Physics," *PTEP*, vol. 2020, no. 8, p. 083C01, 2020.

[2] O. Antipin, M. Redi, A. Strumia, and E. Vigiani, "Accidental composite dark matter," *Journal of High Energy Physics*, vol. 2015, 03 2015.

[3] B. J. Kavanagh and T. D. P. Edwards, "WIMpy_NREFT v1.1 [Computer Software], doi:10.5281/zenodo.1230503. Available at `https://github.com/bradkav/WIMpy_NREFT`," 2018.

[4] B. Ali *et al.*, "Results on photon-mediated dark-matter–nucleus interactions from the pico-60 c_3f_8 bubble chamber," *Phys. Rev. D*, vol. 106, p. 042004, Aug 2022.

[5] J. Buch, J. Fan, and J. S. C. Leung, "Implications of the gaia sausage for dark matter nuclear interactions," *Phys. Rev. D*, vol. 101, p. 063026, Mar 2020.

[6] P. Adhikari *et al.*, "Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the deap-3600 detector," *Phys. Rev. D*, vol. 102, p. 082001, Oct 2020.