Snowmass2021 - Letter of Interest

New Opportunities for Low-Mass Dark Matter Direct Detection With Inelastic Scattering

Thematic Areas:

■ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

Contact Information:
Sumit Ghosh (Texas A&M University) [ghosh@tamu.edu]
Jayden L. Newstead (University of Melbourne) [jayden.newstead@unimelb.edu.au]

Authors: Nicole F. Bell (University of Melbourne), James B. Dent (Sam Houston State University), Bhaskar Dutta (Texas A&M University), Sumit Ghosh (Texas A&M University), Jason Kumar (University of Hawaii), Jayden L. Newstead (University of Melbourne).

Abstract: Recently, there has been intense experimental and theoretical focus on low-mass (sub-GeV) dark matter direct detection. But current studies still leave a wide variety of interesting signals unexplored. One particular interesting signal is inelastic dark matter scattering, which is a generic feature of some classes of models. More detailed studies can explore our ability to determine precise features of dark matter physics from upcoming low-threshold and high-resolution direct detection data sets.

1 Introduction

There has been great recent interest in new experimental strategies for directly detecting the scattering of low-mass (sub-GeV) dark matter (DM) against Standard Model (SM) particles [1–3]. Many of these strategies are aimed at lowering the recoil energy threshold and increasing the energy resolution (perhaps to milli-eV resolution). Studies of these new capabilities have thus far focused on the standard scenarios for DM-SM interactions, such as elastic scattering. But models for low-mass dark matter often produce more involved dark sectors which can yield more interesting signals which can be exploited with new data sets.

For example, inelastic dark matter scattering against nuclei is a generic feature of some classes of low-mass dark matter models [4;5]. Inelastic scattering provides a variety of new signals which can be exploited by new experiments to discover the properties of the underlying dark matter model.

There are several interesting features worth studying.

- The electron recoil spectrum produced by the Migdal effect [6] will depend on the dark matter mass and the mass splitting. This will lead to degeneracies which must be understood before one can determine the properties of the dark matter model from the data.
- If inelastic scattering produces an excited dark matter state which de-excites in the detector by producing photons, then one may find an electron recoil signal [7]. Proposed detectors with milli-eV resolution [8;9] will be able to precisely measure the shape of the photon spectrum, which in turn can be used to constrain the dark matter velocity distribution.
- A promising strategy for direct detection of low-mass dark matter is the search for the relativistic population of DM produced by scattering from cosmic rays [10;11]. This signal is modified significantly if dark matter scattering is inelastic.
- A variety of interesting signatures are correlated with the lifetime of the excited state.

2 Interesting Features of Inelastic Scattering

Motivation. There are classes of low-mass dark matter models for which inelastic scattering is generic. In many scenarios, interactions between the dark sector and SM sector are mediated by a dark photon. Inelastic scattering is then generic if, a) the dark photon couples to a dark sector vector current, and b) the DM is charged only under broken continuous symmetries. If the dark photon couples to a dark matter vector current, then the dark matter must be a complex degree of freedom. But if all of the continuous symmetries under which the DM is charged are spontaneously broken, then this complex degree of freedom is generically split into two real degrees of freedom. Since one cannot construct a vector current for a single real degree of freedom, the dark matter vector current must mix these two real particles, and the dark photon coupling can then only mediate inelastic scattering. Note that if the mass splitting is small, then the only kinematically allowed de-excitation processes involve the emission of photons, neutrinos, or dark sector states.

The Migdal effect. A promising method for probing dark matter-nucleus scattering is through the Migdal effect. But if the scattering is inelastic, then the Migdal electron recoil energy spectrum will depend on the mass and the mass splitting, complicating efforts to determine the properties of the model from the data. As an example, it is straightforward to see that the kinematic endpoint of the electron recoil spectrum is given by $(1/2)\mu v_{max}^2 - \delta$, where δ is the mass splitting, v_{max} is the maximum dark matter speed with respect to the Earth, and μ is the reduced mass of the DM-nucleus system. We thus see that the endpoint has a model degeneracy which is largely independent of the target material, for sub-GeV dark matter. It is necessary for future work to determine the extent to which one can recover the properties of dark matter from the recoil energy spectrum.

Probing de-excitation with high-resolution detectors. If dark matter scatters either in the detector or in the neighboring rock, it can de-excite by producing a photon in the detector ($\chi_2 \to \chi_1\gamma$). This is the scenario of Luminous Dark Matter [12]. Indeed, this scenario could provide an explanation for the XENON1T electron recoil excess [13;14]. If the excited state were at rest, then this photon would be monoenergetic, but since the dark matter has velocity $\beta \sim \mathcal{O}(10^{-3})$, this line signal is actually smeared out. For dark matter of mass m_χ, inelastic upscattering is only kinematically allowed for $\delta \lesssim \beta^2 m_\chi$, and the spread of the photon signal is $\sim \beta\delta$. We thus see that for 100 MeV dark matter, the width of the photon signal could be as large as 100 meV. Upcoming detectors using diamond or silicon carbide as a target could achieve up to meV energy resolution [8;9], implying that they could probe the detailed shape of the photon spectrum. Moreover, from the shape of the spectrum, it is possible to recover the velocity distribution of the excited dark matter particle [7], which in provides indirect information about the incident dark matter particle velocity distribution. It is important to understand in detail the capabilities of high-resolution detectors to probe this scenario.

Cosmic-Ray upscattering. Another strategy for detecting sub-GeV dark matter is to search for the population of relativistic dark matter which is produced by cosmic ray upscattering. Although this population is subdominant, its scattering can produce the leading signal in detectors because the typical nuclear recoils are above threshold. This signal has been studied in detail in the case where scattering is elastic [10;11]. But in the case of inelastic scattering, a variety of new features arise which affect sensitivity, and especially affect the attenuation of the dark matter flux at a deep-underground detector. It is important to clarify these issues, in order to understand the sensitivity of direct detection experiments.

Lifetime of the excited state. If dark matter upscatters to an excited state, the lifetime of the excited state is model-dependent. If the lifetime is sufficiently short, then the initial nuclear scatter and the electron recoils caused by de-excitation photons may be nearly coincident, both spatially and temporally. This signal would not be a pure electron or nuclear recoil, and it is important to ensure that such events not only can pass analysis cuts, but are also calibrated correctly. If the lifetime is longer, then the nuclear recoil and the de-excitation will be spatially and temporally separated. In this case, one could use the spatial and temporal displacement of the two events to determine the velocity of the excited DM particle on an event-by-event basis. This would essentially turn TPC direct detection experiments into directional detectors, whose data could be used to constrain the initial dark matter velocity distribution, and the velocity dependence of the scattering cross section. It would be interesting to study these issues in detail.

3 Conclusion

There has been great recent interest in the direct detection of low-mass dark matter. But current studies have focused mostly on the case of elastic scattering. But inelastic scattering is a generic feature of many classes of dark matter models, and provide interesting phenomenological features. This is an emerging field which is ripe for study during the upcoming Snowmass process.

References

[1] R. Essig, J. Mardon and T. Volansky, Phys. Rev. D **85**, 076007 (2012) [arXiv:1108.5383 [hep-ph]].

[2] P. W. Graham, D. E. Kaplan, S. Rajendran and M. T. Walters, Phys. Dark Univ. **1**, 32-49 (2012) [arXiv:1203.2531 [hep-ph]].

[3] R. Essig, M. Fernandez-Serra, J. Mardon, A. Soto, T. Volansky and T. T. Yu, JHEP **05**, 046 (2016) [arXiv:1509.01598 [hep-ph]].

[4] D. Tucker-Smith and N. Weiner, Phys. Rev. D **64**, 043502 (2001) [arXiv:hep-ph/0101138 [hep-ph]].

[5] D. Tucker-Smith and N. Weiner, Phys. Rev. D **72**, 063509 (2005) [arXiv:hep-ph/0402065 [hep-ph]].

[6] M. Ibe, W. Nakano, Y. Shoji and K. Suzuki, JHEP **03**, 194 (2018) [arXiv:1707.07258 [hep-ph]].

[7] K. K. Boddy, K. R. Dienes, D. Kim, J. Kumar, J. C. Park and B. Thomas, Phys. Rev. D **95**, no.5, 055024 (2017) [arXiv:1609.09104 [hep-ph]].

[8] N. A. Kurinsky, T. C. Yu, Y. Hochberg and B. Cabrera, Phys. Rev. D **99**, no.12, 123005 (2019) [arXiv:1901.07569 [hep-ex]].

[9] S. M. Griffin, Y. Hochberg, K. Inzani, N. Kurinsky, T. Lin and T. C. Yu, arXiv:2008.08560 [hep-ph].

[10] T. Bringmann and M. Pospelov, Phys. Rev. Lett. **122**, no.17, 171801 (2019) [arXiv:1810.10543 [hep-ph]].

[11] J. B. Dent, B. Dutta, J. L. Newstead and I. M. Shoemaker, Phys. Rev. D **101**, no.11, 116007 (2020) [arXiv:1907.03782 [hep-ph]].

[12] B. Feldstein, P. W. Graham and S. Rajendran, Phys. Rev. D **82**, 075019 (2010) [arXiv:1008.1988 [hep-ph]].

[13] E. Aprile *et al.* [XENON], arXiv:2006.09721 [hep-ex].

[14] N. F. Bell, J. B. Dent, B. Dutta, S. Ghosh, J. Kumar and J. L. Newstead, arXiv:2006.12461 [hep-ph].