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Inelastic Boosted Dark Matter at direct detection experiments

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ABSTRACT

We explore a novel class of multi-particle dark sectors, called Inelastic Boosted Dark Matter (iBDM). These models are constructed by combining properties of particles that scatter off matter by making transitions to heavier states (Inelastic Dark Matter) with properties of particles that are produced with a large Lorentz boost in annihilation processes in the galactic halo (Boosted Dark Matter). This combination leads to new signals that can be observed at ordinary direct detection experiments, but require unconventional searches for energetic recoil electrons in coincidence with displaced multi-track events. Related experimental strategies can also be used to probe MeV-range boosted dark matter via their interactions with electrons inside the target material.

1. Introduction

The existence of dark matter (DM), which is advocated by various cosmological and astrophysical observations, is mostly rooted in its gravitational interactions. The strategy of direct detection experiments aims at revealing DM through its possible non-gravitational couplings to Standard Model (SM) particles, mostly by observing a recoiling of target material (henceforth called primary signature) which is induced by *elastic* scattering off of *non*-relativistic DM. A variation in this search scheme is to look for *inelastic* scattering signals, imagining that a DM particle scatters off to an excited state (if kinematically allowed) along with a target recoiling whose spectrum differs from that in the elastic scattering [1]. One may instead focus on secondary visible particles which are potentially involved in de-excitation of the excited state, e.g., X-ray photon in neutrinoless double beta decay experiments [2]. However, it is generally assumed that observing *both* primary and secondary signatures is unlikely due to inadequate DM kinetic energy to overcome the relevant thresholds simultaneously. Many DM direct detection experiments have searched for DM signals, but null observation merely sets stringent bounds on DM models.

These negative results had a profound impact on the field. Traditional experimental searches were designed to target the range of DM masses around 100 GeV and weak-scale scattering cross sections off nuclei, which correspond to the parameter region preferred by Weakly Interacting Massive Particle (WIMP) models. However, these experimental techniques rapidly lose sensitivity below masses of a few GeV and this has ignited a great interest in the exploration of the sub-GeV DM domain. This exploration in the low-mass region is not a simple extrapolation of traditional searches. On the contrary, sub-GeV DM experimental searches are characterized by completely new techniques [3]. The theoretical approach has changed significantly. Instead of building realistic models addressing weak-scale physics and obtaining the DM as a byproduct, the focus is now in inventing new experimental strategies to hunt for DM in unexplored windows of parameter space and propose new signatures, quite distinct from those traditionally looked for. The emphasis today is on the experimental searches, rather than the theoretical model building. The models for sub-GeV DM may superficially appear less ambitious and more *ad hoc* than traditional WIMP models, but their primary role is to motivate interesting and unconventional experimental searches. Moreover, the WIMP assumption of a single DM particle – especially when compared with the complexity of ordinary matter – may be an oversimplification, and the exploration of more complex dark sectors is today well justified. In this paper, we will follow this perspective and propose novel signatures from multi-particle dark sectors that can be looked for at DM direct detection experiments, but that are completely distinct from the traditional expectation.

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The paper is organized as follows. In Sec. 2 we discuss the general strategy while in Sec. 3 we briefly describe the benchmark DM model adopted throughout this paper. We then study key kinematic features in signal events, including energy spectra and decay lengths of visible particles in Sec. 4. Section 5 contains our main results including detection strategy, background consideration, and phenomenology. We summarize our results in Sec. 6. Finally, the appendices are reserved for benchmark DM model details and useful formulae for the scattering and decay processes.

2. General strategy

An alternative approach to traditional searches for DM is offered by the so-called *boosted dark matter* [4]. The underlying DM models hypothesize a dark sector comprising of two DM species with a hierarchical mass spectrum: the heavier and the lighter species are denoted by χ_0 and χ_1, respectively.[1] Typical scenarios assume that χ_0 has no direct coupling to SM particles but pair-annihilates into two χ_1's which directly communicate with SM particles. Their respective relic abundances are determined by the "assisted" freeze-out mechanism [5] rendering the heavier (lighter) a dominant (sub-dominant) DM component. In the present universe, the *boosted* χ_1 can be produced via pair-annihilation of χ_0 in the galactic halo, leading to a total flux [4]

$$\mathcal{F} = 1.6 \times 10^{-4}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \left(\frac{\langle \sigma v\rangle_{0\to 1}}{5\times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}\right)\left(\frac{\mathrm{GeV}}{m_0}\right)^2, \tag{2.1}$$

where the reference value for $\langle\sigma v\rangle_{0\to1}$, the velocity-averaged annihilation cross section of $\chi_0\chi_0 \to \chi_1\chi_1$, corresponds to a correct DM thermal relic density for χ_0. Although here we focus on multi-particle DM sectors, boosted DM (which was also considered in Ref. [6]) can be alternatively obtained in the universe today in models with Z_3 symmetry through the semi-annihilation process, e.g., $\chi_0\chi_0 \to \chi_0\phi$ where ϕ stands for either a SM or an exotic particle lighter than the DM χ_0 [4,7,8].

For χ_0 of weak-scale mass (i.e., ~ 100 GeV), the incoming flux of lighter DM χ_1 (near the earth) is as small as $\mathcal{O}(10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1})$ so that large volume neutrino detectors such as Super-Kamiokande, Hyper-Kamiokande, and Deep Underground Neutrino Experiment are preferred in search for elastic signatures [4,8–10] or inelastic signatures [11]. Very recently, the Super-Kamiokande Collaboration has reported the first result in search for high energetic electrons (≥ 0.1 GeV) induced by elastic scattering-off of boosted DM χ_1 [12]. Related searches can be conducted at fixed target experiments, with active production of boosted dark matter [11,13–15].

On the other hand, if the dominant relic component χ_0 takes a mass in the sub-GeV regime, the large-volume neutrino detectors mentioned above may not be ideal to look for the signatures by χ_1 due to their relatively high threshold energies (e.g., several tens to a hundred MeV). Moreover, noting from Eq. (2.1) that the χ_1 flux is inversely proportional to the mass square of χ_0, we observe that it can increase by 4–6 orders of magnitude with sub-GeV/GeV-range χ_0 DM, while the resulting relic density is still in agreement with the current measurement. Hence, it is quite natural to pay attention to relatively small (fiducial) volume detectors *but* with a low threshold energy: for example, conventional DM direct detection experiments. We will show that current and future DM direct detection experiments such as XENON1T [16,17], DEAP-3600 [18–20], and LUX-ZEPLIN (LZ) [21] may possess sufficient sensitivity to signals caused by boosted (lighter) DM of MeV-range mass. A beginning effort was made in Ref. [22]; the authors assumed coherent scattering of nuclei by the boosted DM which arises in leptophobic scenarios (e.g., gauged baryon number or Higgs portal models), and reinterpreted the results from even smaller-volume detectors like LUX.

[1] The stability of each of them is ensured by two separate symmetries such as $Z_2 \times Z_2'$ or $\mathrm{U}(1)' \times \mathrm{U}(1)''$. See, for example, the model in Ref. [5].

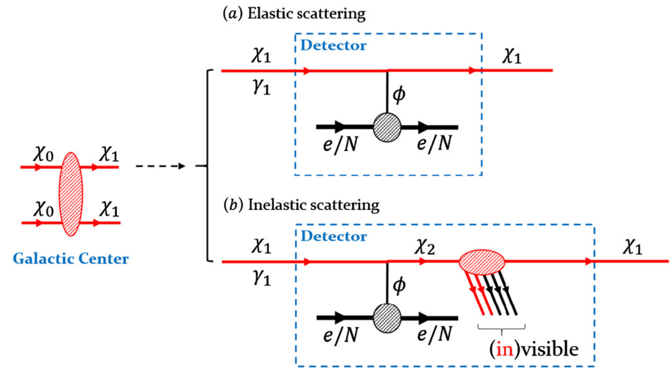

Fig. 1. The ordinary boosted DM (upper part) and iBDM (lower part) scenarios with the relevant DM-signal processes under consideration.

However, as we will discuss later, we observe that the MeV-range χ_1-electron scattering can compete with the corresponding interaction with nucleons, unless the coupling associated with the electron is suppressed in specific model frameworks. Therefore, a dedicated study on boosted light χ_1-induced signatures involving the electron recoil (ER) is also required in probing boosted DM scenarios at conventional direct detection experiments, in which ordinary ER (lying in the keV to sub-MeV regime) is usually rejected due to a large rate of expected backgrounds. However, we claim that the signal induced by boosted DM can be quite energetic (above a few to tens of MeV) and usually leaving an appreciable track in the detector system, which is clearly distinctive from conventional background events associated with ER. In this sense, DM direct detection experiments should be highlighted as *discovery machines* of light boosted DM.

In this paper, we explore Inelastic Boosted Dark Matter (iBDM) as a novel paradigm for DM and discuss the characteristic signals that can be produced at direct detection experiments. We take a comprehensive approach, considering both elastic and inelastic scatterings of *boosted* DM which are displayed in the upper and the lower panels of Fig. 1, correspondingly. In particular, the latter possibility involves the process in which an incident DM particle χ_1, produced by pair-annihilation of heavier DM χ_0 (at say, the Galactic Center) with a boost factor $\gamma_1 = m_0/m_1$, scatters off to a *heavier, unstable* dark sector particle χ_2 together with a target recoil (e or p) via a mediator ϕ exchange. This is what we refer to as primary process. The χ_2 then disintegrates back into χ_1 and some other decay products which may include SM particles. This is called the secondary process. If (at least) part of the secondary signature is observable in the same detector complex (blue dashed boxes in Fig. 1), the correlation between the primary and the secondary processes can be an additional, powerful handle to identify DM events from backgrounds as well as to distinguish the iBDM scenario from ordinary boosted DM (elastic channel). Furthermore, the secondary signal can be substantially displaced from the primary vertex over the position resolutions of the detector, depending on the parameter choice; this can be considered as unambiguous evidence for an inelastic scattering process. From all the considerations above, we expect that good sensitivity to DM signals with ER can be achieved at current and future DM direct detection experiments.