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Physics Opportunities with Inelastic Boosted Dark Matter in the Next-Generation Large-Mass Neutrino and Dark Matter Experiments

NF Topical Groups:

■ (NF3) Beyond the Standard Model

CF Topical Groups:

■ (CF1) Dark matter: particle-like

TF Topical Groups:

■ (TF08) BSM model building
■ (TF09) Astro-particle physics & cosmology

Contact Information:
Doojin Kim (Texas A&M University) [doojin.kim@tamu.edu]

Authors: Haider Alhazmi, Joshua Berger, Hector Carranza, Animesh Chatterjee, Albert De Roeck, Gian Giudice, Chang Hyon Ha, Lucien Heurtier, Wooyoung Jang, Doojin Kim, Kyoungchul Kong, Hyun Su Lee, Pedro A. N. Machado, Zahra Gh. Moghaddam, Gopolang Mohlabeng, Jong-Chul Park, Seodong Shin, Leigh H. Whitehead, and Jaehoon Yu

Abstract: This Letter of Interest discusses a class of new dark-sector scenarios beyond WIMP, the model of inelastic boosted dark matter, its phenomenological implications, and related physics opportunities, in particular, at various ongoing and near-future large-mass neutrino and dark matter detectors, as an important aspect of both the neutrino physics program and the dark matter physics program in the coming decade and beyond.

Introduction: Dark matter is a compelling observational motivation for physics beyond the Standard Model (SM). Over the decades, an enormous amount of experimental effort has been made in the search for dark matter through its hypothetical non-gravitational interactions with ordinary matter, for example, dark matter direct/indirect detection and accelerator-based experiments, mostly focusing on weakly interacting massive particles (WIMPs). However, the null observation of conclusive signals offers an opportunity to contemplate alternative ideas and methods for searching for dark matter signals. While an increasing number of new ideas have been proposed recently in light of this situation, we here discuss a model of inelastic boosted dark matter (iBDM)[1] and related physics opportunities[1–9], in particular, in ongoing/near-future large-volume neutrino[1;4–8] and dark matter direct detection experiments[3;7;9].

We remind the reader that the conventional dark matter direct detection experiments aim to observe a *nucleus* recoil caused by an *elastic* scattering of *non-relativistic* dark matter with a *weak-scale* mass. By contrast, the iBDM models allow for an alternative approach based on different assumptions, that is, *inelastic* scattering processes of *boosted* (i.e., *relativistic*) dark matter produced in the universe *today*, with a *non-weak-scale* mass (e.g., keV to sub-GeV range) in channels with an *electron* or *nucleon* recoil. Here, the inelastic scattering processes assume that the associated dark sector contains additional particles that can be produced by the upscattering of BDM. Such other particle(s) can then decay back into dark matter and possibly additional visible particles in the detector. Therefore, the expected signal processes come with several features on top of the usual target recoil that potential backgrounds are much less likely to mimic. To capture the signal features and hence enhance the signal sensitivity, experiments with high-capability detectors, e.g., DUNE, are particularly well suited to iBDM signal searches.

Models of inelastic boosted dark matter: Models of iBDM have two dark matter particles, as is usual for BDM models. One of the two dark matter particles (typically, the heavier one χ_0) does not directly interact with the SM particles, whereas the other one, say χ_1, could directly couple to the SM particles. On the other hand, interactions between χ_0 and χ_1 are allowed; for example, χ_0 may pair-annihilate to a χ_1 pair. The χ_0 and χ_1 relic abundances can be (other possibilities exist though this is particularly well-motivated) governed by the "assisted freeze-out" mechanism[10]. Due to the model setup, χ_0 is not in direct contact with the thermal bath, but has thermalized through the "assistance" of χ_1. Typically, χ_0 froze out earlier, becoming the dominant relic, while χ_1 froze out later, constituting a negligible amount of the overall dark matter abundance. The standard dark matter direct detection experiments are typically not sensitive yet to detect either χ_0 or χ_1 because of suppressed coupling to SM and small relic contribution, respectively. However, χ_1 can be *boosted* by pair-annihilation of non-relativistic χ_0 in the present universe (e.g., galactic halo, see the l.h.s. of Fig. 1), so searching for relativistic scattering signatures induced by boosted χ_1 provides a new direction to explore dark matter physics[11].

The iBDM model contains another dark-sector species, χ_2, that is heavier than χ_1 and has coupling to χ_1 via a mediator X, e.g., a dark photon, which also mediates the interactions between χ_1 and the SM particles. The existence of χ_2 can give rise to significantly different experimental signatures from both elastic BDM and neutrino neutral-current scattering signals. We envision the situation that boosted χ_1 scatters off either an electron or nucleon in the detector, producing a χ_2 (henceforth called primary scattering) that subsequently decays back to χ_1 and a SM fermion pair (e.g., e^+e^-) via an on-/off-shell mediator within the detector fiducial volume (henceforth called secondary decay). So, the final state of generic iBDM events has features from multiple visible particles, i.e., primary target recoil plus secondary visible particles (see the r.h.s. of Fig. 1). Moreover, the secondary decay can be displaced from the primary scattering vertex, depending on the model parameter choices. Therefore, the experimental signatures of iBDM have a rich structure which can be not only distinguished from potential backgrounds but analyzed with conventional collider techniques[1].

iBDM searches in neutrino experiments: In a wide range of parameter space where the mass of the heavy

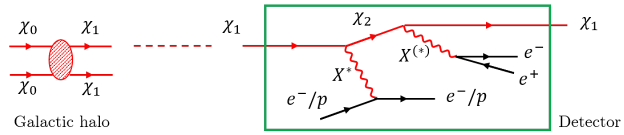

Figure 1: An example iBDM signal process. See the text for details.

dark matter χ_0 lies in a similar range as the WIMP mass, the expected flux of BDM χ_1 produced within the galaxy is not large enough for conventional dark matter direct search detectors to have sensitivity to the BDM signal including iBDM[11]. By constrast, many of the terrestrial neutrino detectors such as DUNE, ProtoDUNE, Super-/Hyper-K, and IceCube/DeepCore/PINGU are featured by $\gtrsim$ kton-scale fiducial mass, so they possess sufficient signal sensitivity. Several iBDM sensitivity studies have been performed for several neutrino detectors, e.g., Super-/Hyper-K[1;7], DUNE[1;7;8], ProtoDUNE[4], and DeepCore[7], and show that these experiments can provide complementary information, covering different regions of model parameter space[7]. In addition, balloon-type neutrino detectors, e.g., ANITA, can address ultra-energetic iBDM signals[6].

We point out that highly capable detectors adopting, for example, LArTPC technology can provide excellent particle identification, particle track measurement, low energy threshold, and high resolutions in energy, angle and position measurements and can capture full features of iBDM signals. Thus even surface-based experiments such as ProtoDUNE are capable of identifying iBDM events although they are fully exposed to cosmic-ray-induced backgrounds[4]. ICARUS of SBN is a promising experiment for searching for iBDM signals in the immediate future along this line. Also, a recent dedicated sensitivity study at a DUNE-like detector with parameterized detector effects suggests that these detectors provide opportunities to probe unexplored dark-photon parameter space and that their sensitivity reaches are competitive, owing to great background rejection[8], in both model-dependent and model-independent fashions.

iBDM searches in ton-scale dark matter experiments: Recently commissioned and near-future ton-scale dark matter direct search detectors can be sensitive to the iBDM signals[3;7] when the heavy dark matter χ_0 is lighter than the conventional WIMP, i.e., below $\mathcal{O}$(GeV), hence resulting in an enhanced flux of the light BDM χ_1. In particular, the multi-particle feature of the iBDM signal again allows to achieve an enhanced signal identification, hence improved sensitivity reaches[3]. Inspired by these advantages, the first iBDM search was conducted by the COSINE-100 Collaboration[12], and the expected sensitivity reaches were estimated for various dark matter detectors such as XENON1T[3], DEAP3600[3], LZ[3], and DarkSide-20k[7].

Indeed, the recent anomaly reported by the XENON Collaboration[13] carries an intriguing implication for the iBDM model. Giudice et al.[3] discussed, for the first time, that XENON1T would be sensitive to BDM interacting with electrons, and a recent follow-up study[9] demonstrated that iBDM models contain parameter regions to accommodate the XENON1T excess successfully while the model parameters are consistent with existing limits. If confirmed, the XENON1T anomaly can be the first signal to indicate that the associated dark sector is non-conventional, opening a new pathway toward dark matter phenomenology. As such, iBDM can provide benchmark guidance to understand non-conventional dark sector physics, and searching for iBDM signals at future dark matter detectors (e.g., COSINE-200, LZ, XENONnT, DarkSide-20k) will be an exciting scientific program in the next decade.

Summary: The notion of new dark-sector scenarios beyond WIMP, which are receiving increasing attention in the high-energy physics community, can provide alternative avenues in shining light on dark matter. Models of inelastic boosted dark matter provide an interesting possibility in this spirit and can be tested at various ongoing/near-future large-mass neutrino and dark matter detectors ranging from ton to Gton scale. Given phenomenological implications and testability of iBDM, it will be an important aspect of both the neutrino physics program and the dark matter physics program in the upcoming decade.

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