Snowmass2021 - Letter of Interest

Multi-scattering Dark Matter at Neutrino Experiments

NF Topical Groups:

■ (NF3) BSM

CF Topical Groups:

■ (CF1) Dark Matter: Particle Like

TF Topical Groups:

■ (TF8) BSM Model Building
■ (TF9) Astro-particle physics & cosmology

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Abstract:
In models with heavy dark matter (DM), the interaction cross section in a detector can be large enough to induce multiple hits as the DM traverses the detector. This unique signal can be looked for not only in traditional direct detection experiments, but also in neutrino experiments with a large-volume detector. Furthermore, in a wide range of macroscopic dark matter (MDM) models, additional interaction processes can occur, including radiative capture of nuclei. In this Letter, we discuss the prospects for testing these scenarios at ongoing and upcoming dark matter and neutrino experiments.

Introduction. It is frequently assumed that dark matter (DM) masses are small compared to those of macroscopic objects, as well as that DM is point-like on nuclear and larger scales. On the other hand, we know of several classes of extended objects that can arise in quantum field theory that could serve as DM candidates, including topological [1] and non-topological [2–5] solitons, dark quark nuggets [6–9], dark blobs [10], and dark magnetic monopoles [11–14]. Such DM candidates that are not made of point-like particles can also have much larger masses, up to macroscopic sizes.

The phenomenology of macroscopic dark matter (MDM) built out of these extended objects could be very different from that of point-like DM. More massive DM candidates more sparsely populate the galaxy, so that their interaction strength can be drastically larger and still remain consistent with current searches. Such MDM may therefore interact multiple times in a detector [5;15–17]. These interactions could be elastic scattering events. Additional interactions are also possible if the MDM has an extent size much larger than the de Broglie wavelength corresponding to the center of momentum motion, which is of order 10^{-14} m in the limit that the MDM is much more massive than the nuclei in the detector. In this case, the structure of the MDM is probed and new scattering modes can be important. In particular, for models in which interactions of the MDM induce a macroscopic region that is electroweak symmetric (EWS), such as EWS dark matter balls (EWS-DMB) [5] or EWS dark monopoles [14], the EWS region acts as an effective potential well for nuclei. A MDM object passing through a detector can therefore radiatively capture nuclei, forming an MDM-nucleus bound state while emitting photons. Several photons may be emitted as the excited bound state that is formed de-excites down the ground state. Furthermore, several such capture events can occur as the MDM traverses a detector. In this Letter, we explore the prospects for detection of MDM at current and upcoming experiments.

Models. Candidates for MDM can arise in several simple scenarios. In this Letter, we focus on candidates that generate a potential well for nuclei.

A well-studied mechanism for generating such a potential arises in models in which the MDM creates a region in which the electroweak vacuum is modified. It has been recently shown that non-topological solitons can lead to such a region [5]. Non-topological solitons, which are stable extended configurations of a field, were proposed long ago [3–5] and can arise in generic BSM models. By coupling the field making up the soliton to the Higgs via the Higgs portal, the solitonic field configuration creates a macroscopic spherical EWS region. Furthermore, it has been demonstrated that such EWS-DMBs can be produced in the early universe during a first order electroweak phase transition and come to make up the DM today. EWS-DMB production depends sensitively on the Higgs portal coupling, which has to be sufficiently large to generate the solitonic configuration, leading to a finite range of masses in the 1 to 10^{10} g range. The energy density of the EWS-DMBs is of order the electroweak scale, leading a range of radii 10^{-9} cm to 10^{-6} cm.

The scenario described above is a simple proof-of-principle example. Other scenarios, e.g. ones in which the QCD phase is modified in a macroscopic region, are possible and we do not restrict ourselves to a particular scenario in describing the phenomenology and experimental search prospects below.

Radiative Capture Phenomenology. Based on the EWS-DMB scenario, noting that such phenomena are possible in other models, we consider that the MDM induces a potential well for nuclei. In the case of the EWS-DMB, this occurs because the EWS region modifies the mass of the nucleus within the EWS-DMB; the modified nuclear mass acts as a potential. Provided that this potential is sufficiently deep, MDM and nuclei can combine to form bound states [18]. The formation of these bound states is analogous to radiative neutron capture. In the initial capture process, a photon is emitted corresponding to the binding energy of the bound state formed, which is expected to be of order 100 MeV [5;18] in the case of EWS-DMBs. Furthermore, it has been shown that excited states of the system are typically populated in the initial capture process [18]. The de-excitation cascade down to the ground state of the system leads to additional photons. This process of nuclear capture can occur multiple times as the MDM traverses a detector. The target signal is therefore a line along the MDM trajectory of nuclear capture events that each produce several photons. The radiative capture cross section has been calculated[18] and, in the large radius limit, shown to scale as $R^{1/2}$, where R is the radius of the MDM.

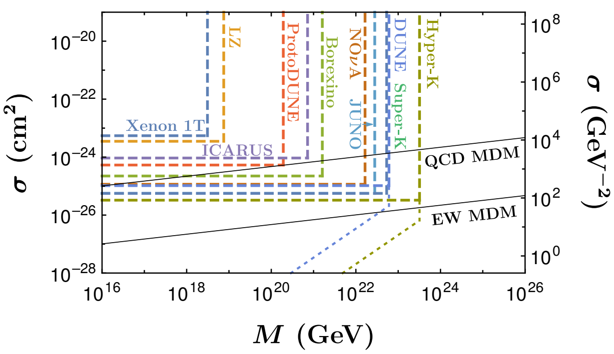

Figure: Projected sensitivity to heavy DM at several different direct detection and neutrino experiments. The dashed lines denote parameter space in which at least 5 interactions occur during MDM passage through the detector and at least one such passage occurs during the running time of the detector (10 years for Borexino, Super-Kamiokande, DUNE, and Hyper-Kamiokande; 5 years for ICARUS and NOνA; one year at the direct detection experiments and ProtoDUNE). The dotted lines indicate regions in which at least one radiative capture event is expected.

Experimental Sensitivity. A large, sensitive detector can look for elastic scattering or nuclear capture processes from relic DM traversing the detector. The main parameters of this model that determine the experimental sensitivity are the mass and cross section of the DM. For radiative capture, the bound state structure of the MDM-nucleus system may also play an important role. The larger the mass, the more sparsely the DM populates the solar system and the more rarely an DM particle encounters the detector. The smaller the cross section, the fewer radiative capture events occur as DM traverses the detector. The sensitivity to large masses and small radii is therefore enhanced for larger detectors.

The signal can be looked for in any large, dense detector that has a sufficiently low threshold. This could include liquid scintillator, water Cherenkov, and liquid argon time-projection chamber (LArTPC) detectors. Thus, both DM direct detection and neutrino experiments can have sensitivity.

In initial studies of the radiative nuclear capture process[5;18], it has been assumed that the signal is sufficiently striking that a single MDM traversing a detector and leading to at least five nuclear capture events in the detector would lead to a discovery. The sensitivities determined in this way are shown in the figure, assuming the same requirement for any interaction mechanism. A set of direct detection and neutrino experiments is presented. We display the one year sensitivity of a current large direct detection experiment, Xenon1T[19], as well as a forthcoming direct detection experiment, LZ[20]. We further present, with assumed running time in square brackets, current neutrino detectors that use liquid scintillators (Borexino[21] [10 years] and NOνA[22] [5 years]), water Cherenkov sensors (Super-Kamiokande[23] [10 years]), and LArTPCs (ICARUS[24] [5 years] and ProtoDUNE[25] [1 year]). With an eye toward future experiments, we project the 10 year sensitivity of JUNO[26], Hyper-Kamiokande[27], and DUNE[28].

Next Steps. The signal discussed in this Letter is novel and requires further experimental study. While the structure of the signal is rather unique, it will be important to consider backgrounds and impediments to reconstruction from cosmic rays for surface detectors. It will further be important to design an appropriate trigger to make sure that such events are recorded in the first place. Reconstruction of the particles could be tricky if the energy of the recoiling nucleus or the photons released in the nuclear capture process is close to the detection threshold. Finally, should such events be observed, it will be interesting to see if the unique structure of a line of nuclear captures can be reconstructed. LArTPC detectors in particular may offer a highly detailed picture of the trajectory of a DM particle through the detector.

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