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Isospin-Violating Dark Matter Benchmarks for Snowmass 2013

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Isospin-violating dark matter (IVDM) generalizes the standard spin-independent scattering parameter space by introducing one additional parameter, the neutron-to-proton coupling ratio f_n/f_p. In IVDM the implications of direct detection experiments can be altered significantly. We review the motivations for considering IVDM and present benchmark models that illustrate some of the qualitatively different possibilities. IVDM strongly motivates the use of a variety of target nuclei in direct detection experiments.

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I. INTRODUCTION

The standard presentation of direct detection experimental results for spin-independent scattering is in the (m_X, σ_p) plane, where m_X is the mass of the dark matter particle X, and σ_p is the X-proton scattering cross section. However, direct detection experiments do not directly constrain σ_p. Rather, they bound scattering cross sections off of nuclei. Results for nuclei are then interpreted as bounds on σ_p by assuming that the couplings of dark matter to protons and neutrons are identical, *i.e.*, that the dark matter's couplings are isospin-invariant.

This assumption is valid if the interaction between dark matter and quarks is mediated by a Higgs boson, as in the case of neutralinos with heavy squarks. In general, however, it is not theoretically well-motivated: the assumption is violated by many dark matter candidates, including neutralinos with light squarks, dark matter with Z-mediated interactions with the standard model (SM), dark matter charged under a hidden U(1) gauge group with a small kinetic mixing with hypercharge, and dark matter coupled through new scalar or fermionic mediators with arbitrary flavor structure. In the next ten to twenty years, during which many direct detection experiments will be searching for dark matter, it is clearly desirable to consider frameworks that can accommodate these more general possibilities.

Isospin-violating dark matter (IVDM) [1–6] provides a simple framework that accommodates all these possibilities by including a single new parameter, the neutron-to-proton coupling ratio f_n/f_p. One might have expected an overarching framework to need many more parameters. However, for spin-independent scattering with the typical energies of weakly-interacting massive particle (WIMP) collisions, the dark matter does not probe the internal structure of nucleons. Loosely speaking, dark matter sees nucleons, but not quarks. Nucleons are therefore the correct "effective degrees of freedom" for spin-independent WIMP scattering, and IVDM therefore captures all of the possible variations by letting the proton couplings differ from the neutron couplings.

Although a simple generalization, IVDM can drastically change the interpretation of data from direct detection experiments. This aspect has been highlighted with respect to data at low mass ($5-20$ GeV), in which several potential signals have been reported (DAMA [7], CoGeNT [8, 9], CRESST [10], and CDMS-Si [11]) and several bounds have been placed (CDMS-Ge [12, 13], Edelweiss [14], XENON10 [15], and XENON100 [16, 17]). With the assumption of isospin invariance, many of the signal regions of interest (ROIs) do not overlap, and almost all of the ROIs are excluded by null results from other experiments. The assumption of isospin invariance is especially unmotivated for low-mass dark matter since isospin invariance is primarily motivated by neutralino dark matter, which cannot explain the low-mass data in standard supersymmetric frameworks. Although IVDM does not make it possible to reconcile all of the existing data at present, it can alter the standard picture drastically, and its implications for low-mass dark matter, although not the primary reason to consider IVDM, illustrate well how different the sensitivities of various experiments may be once the assumption of isospin invariance is relaxed.

II. FORMALISM

Dark matter-nuclei scattering is largely coherent, which for isospin-invariant scenarios produces a well-known A^2 enhancement to the cross section, favoring scattering off heavier elements. But in the case of isospin-violation, destructive interference can instead suppress the scattering cross section. Although direct detection experiments typically present results in terms of σ_p, the actual quantity reported is the *normalized-to-nucleon cross section* σ_N^Z, which is the dark matter-nucleon scattering cross section that is inferred from the data of a detector with a target with Z protons, assuming isospin-invariant interactions. This quantity is related to σ_p by the "degradation factor" [6]

$$D_p^Z \equiv \frac{\sigma_N^Z}{\sigma_p} \; = \; \frac{\sum_i \eta_i \mu_{A_i}^2 [Z + (f_n/f_p)(A_i - Z)]^2}{\sum_i \eta_i \mu_{A_i}^2 A_i^2} \, , \tag{1}$$

where η_i is the natural abundance of the i^{th} isotope, $\mu_{A_i} = m_X m_{A_i}/(m_X + m_{A_i})$ is the reduced mass of the dark matter-nucleus system, and f_n and f_p are the couplings of dark matter to neutrons and protons, respectively. For isospin-invariant interactions, $f_n = f_p$, and $\sigma_N^Z = \sigma_p$.

Although σ_p is not directly measured, a determination of the normalized-to-nucleon cross section by two detectors with different targets provides a measurement of $\sigma_N^{Z_1}/\sigma_N^{Z_2} = D_p^{Z_1}/D_p^{Z_2}$. From Eq. (1), this quantity depends quadratically on f_n/f_p. Measurements of the normalized-to-nucleon cross section by two experiments with different targets are thus sufficient to determine f_n/f_p up to a two-fold ambiguity. A measurement with a third target material is required to break this degeneracy.

III. BENCHMARKS

Absent any prejudice, f_n/f_p is a free parameter that must be constrained by data, no different than the mass and cross section. But we can identify some benchmark values of f_n/f_p that are particularly noteworthy:

1. $f_n/f_p = -13.3$ ("Z-mediated"): Valid for dark matter with Z-mediated interactions with the SM.
2. $f_n/f_p = -0.82$ ("Argophobic"): For this value, the sensitivity of argon-based detectors is maximally degraded. Note that potential CoGeNT and CDMS-Si signals can be made consistent for $f_n/f_p = -0.89$ [6]. (The other region for which these signals can be consistent includes the isospin-invariant case.)
3. $f_n/f_p = -0.70$ ("Xenophobic"): For this value, the sensitivity of xenon-based detectors is maximally degraded.
4. $f_n/f_p = 0$ ("Dark photon-mediated"): Valid for dark matter that interacts with the SM through kinetic mixing with the photon.
5. $f_n/f_p = 1$ ("Isospin-invariant"): Valid for dark matter that interacts with the SM through Higgs exchange.

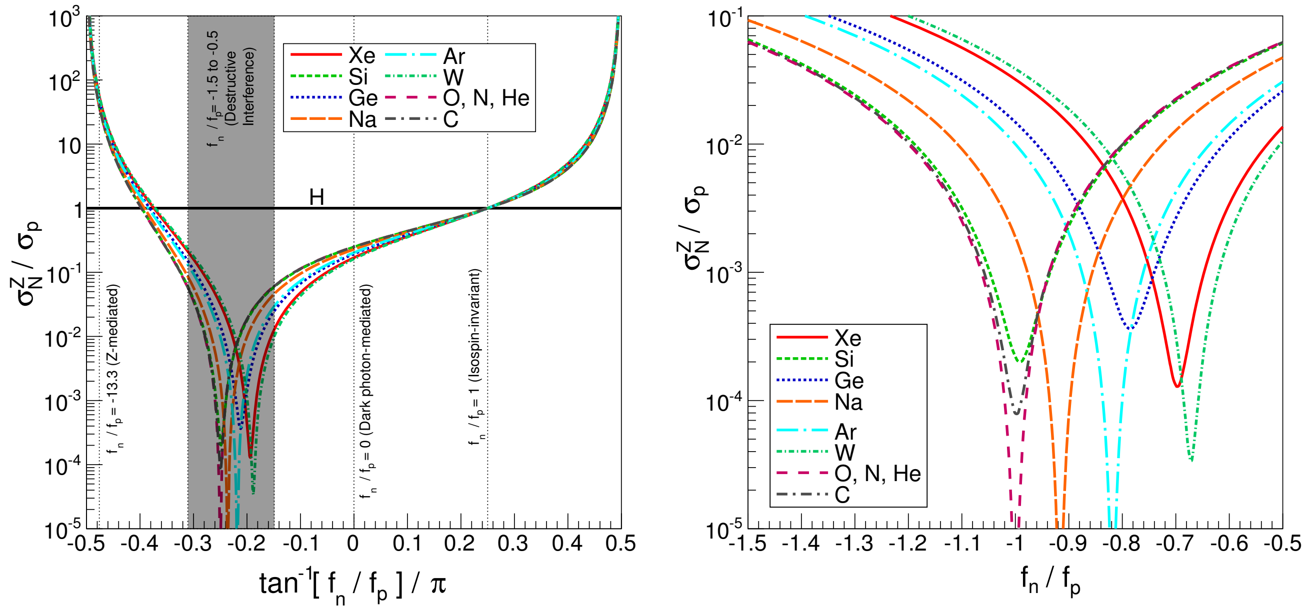
IV. IMPACT ON DIRECT DETECTION

In Fig. 1 we plot σ_N^Z/σ_p as a function of f_n/f_p for many of the target materials commonly used for direct detection experiments. The full range of f_n/f_p is shown in Fig. 1(a) and the destructive interference region ($-1.5 \leq f_n/f_p \leq -0.5$) is shown in Fig. 1(b). For materials with only one isotope with significant abundance, such as oxygen, nitrogen, helium, sodium, and argon, it is possible to almost completely eliminate the detector's response with a particular choice of f_n/f_p. But for a material such as xenon, with many isotopes, it is not possible to cancel the response of all isotopes simultaneously. For materials such as carbon, silicon, germanium, xenon, and tungsten, the maximum factor by which their sensitivity to σ_p may be degraded is within the range $10^{-5} - 10^{-3}$.

Figure 2 shows relevant direct detection constraints and possible signals in the dark matter mass range $5 - 20$ GeV. For the isospin-invariant case shown in Fig. 2(a), $f_n/f_p = 1$, XENON100 results [17] place stringent constraints on the parameter space. On the other hand, for the xenophobic value $f_n/f_p = -0.70$ shown in Fig. 2(b), the CDMS-Si ROI almost entirely evades the XENON100 bound, and the ROIs from CoGeNT [8] and an ROI from an independent reanalysis of CDMS-Ge data [18] become marginally consistent with the XENON100 bound. However, the DAMA [7] and CRESST [10] ROIs remain in tension with XENON100 bounds for $f_n/f_p = -0.70$, and the agreement between CDMS-Si and the CoGeNT and CDMS-Ge results is weakened.

V. COMPLEMENTARY ASTROPHYSICAL AND COLLIDER PROBES

IVDM models can also be probed through monojet/monophoton collider searches [6, 22–24] and indirect detection searches using the galactic center, galactic halo, dwarf spheroidals, etc. as sources [23, 25, 26]. To compare sensitivities, one typically considers a particular dark matter-parton interaction structure that generates spin-independent



(a) Entire f_n/f_p range

(b) Destructive interference region

FIG. 1: Ratio of σ_Z^N to σ_p for materials relevant to direct detection experiments [6]. Ratios are shown as a function of f_n/f_p for (a) the entire range of couplings and (b) the destructive interference region. We have made the mild assumption that the reduced masses μ_{A_i} are all equal for a given element and dark matter mass.

scattering and reproduces direct detection data for a particular choice of f_n/f_p. Crossing symmetry is then used to determine the dark matter annihilation or collider production cross section.

For IVDM with destructive interference, to maintain the same direct detection cross sections, the individual couplings to first generation quarks must be enhanced, which implies enhanced cross sections for dark matter annihilation and dark matter production at colliders. Moreover, both indirect and collider searches tend to have greater sensitivity to low-mass dark matter. At the same time, it is important to note that indirect detection bounds are weakened if the dark matter-parton interaction structure permits only P-wave annihilation, and both collider and indirect detection sensitivities are weakened if dark matter couples to a light mediator.

Other interesting complementary probes of IVDM arise from searches for neutrinos arising from dark matter annihilation in the sun [27–29]. If the dark matter scattering and annihilation processes in the sun are in equilibrium, the neutrino event rate is directly related to the dark matter solar capture rate, which in turn is proportional to the cross section for dark matter to scatter off solar nuclei. Since the sun is dominated by elements with small numbers of neutrons, it provides targets that are complementary to targets like germanium and xenon.

VI. CONCLUSIONS

The main motivation for isospin-violating dark matter is theoretical. Dark matter with a mass $\gtrsim 1$ GeV does not probe the internal structure of nucleons, but does probe the nucleon structure of nuclei; a framework that treats the dark matter coupling to protons and neutrons as independent parameters is thus the most natural framework for describing dark matter interactions. Isospin-violating interactions can have a large impact on the way direct detection data is interpreted, potentially helping to reconcile some of the seemingly inconsistent data from direct detection experiments at low mass. A complete determination of the isospin structure of dark matter interactions would require data from at least three direct detection experiments with different targets. However, data from indirect detection or collider searches can potentially provide complementary data that can help determine f_n/f_p, especially at low mass.

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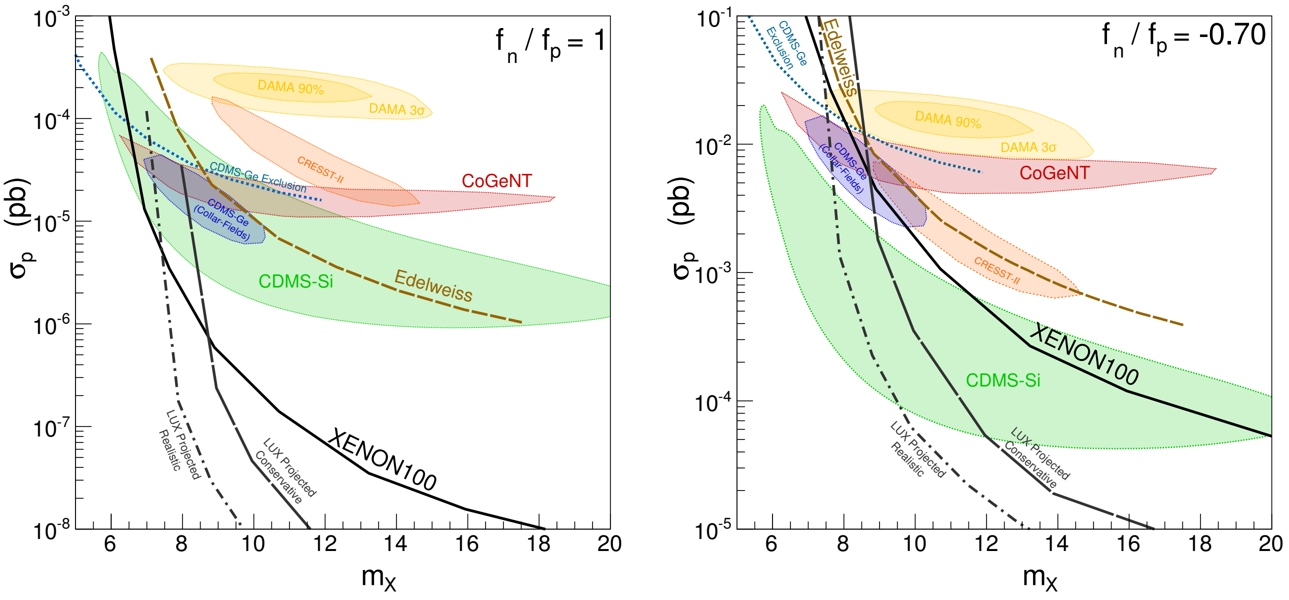

(a)

(b)

FIG. 2: Light dark matter experimental results in the (m_X, σ_p) plane for (a) the isospin-invariant case $f_n/f_p = 1$ and (b) the xenophobic case $f_n/f_p = -0.70$ [6]. Plotted are 90% CL ROIs for CoGeNT [8], CRESST [10], CDMS-Si [11], an ROI for an independent analysis of CDMS-Ge data [18], the 90% and 3σ ROIs for DAMA [7] as determined in Refs. [19, 20]. Exclusion contours from CDMS [13], Edelweiss [14], and XENON100 [16, 17] are also shown, as are projected bounds from LUX [21].

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