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Authors

Feng, Jonathan L
Kumar, Jason
Marfatia, Danny
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Isospin-violating dark matter

Jonathan L. Feng^{a,*}, Jason Kumar^b, Danny Marfatia^{c,d}, David Sanford^a

^a Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

^b Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA

^c Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA

^d Department of Physics, University of Wisconsin, Madison, WI 53706, USA

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ABSTRACT

Searches for dark matter scattering off nuclei are typically compared assuming that the dark matter's spin-independent couplings are identical for protons and neutrons. This assumption is neither innocuous nor well motivated. We consider isospin-violating dark matter (IVDM) with one extra parameter, the ratio of neutron to proton couplings, and include the isotope distribution for each detector. For a single choice of the coupling ratio, the DAMA and CoGeNT signals are consistent with each other and with current XENON constraints, and they unambiguously predict near future signals at XENON and CRESST. We provide a quark-level realization of IVDM as WIMPless dark matter that is consistent with all collider and low-energy bounds.

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1. Introduction

Dark matter makes up five-sixths of the matter in the Universe, but all current evidence for dark matter is through its gravitational effects. The detection of dark matter scattering through non-gravitational interactions would be a large step toward identifying dark matter, and there are many experiments searching for such events. The excitement around this approach has been heightened recently by data from the DAMA [1] and CoGeNT [2] experiments, which are consistent with scattering by a dark matter particle with mass $m_\chi \sim 10$ GeV and spin-independent (SI) X -nucleon scattering cross sections $\sigma_N \sim 2 \times 10^{-4}$ pb and 5×10^{-5} pb, respectively. This excitement is, however, tempered by null results from XENON [3, 4] and CDMS [5,6], leaving a confusing picture that has motivated much theoretical and experimental work.

The comparison of dark matter experimental results is subject to an array of assumptions and uncertainties from particle physics, nuclear physics, and astrophysics. In this study, we focus on a particularly simple and common particle physics assumption, that of flavor isospin invariance. Dark matter detectors have various nuclear compositions. To derive implications for σ_N , experiments almost universally assume that dark matter couples identically to protons and neutrons. This assumption is not well motivated. For example, Dirac neutrinos and sneutrinos have isospin-violating

couplings, and, in fact, even neutralino couplings are generically isospin-violating, although typically at insignificant levels (see, e.g., Refs. [7,8]). In any case, as these and other conventional dark matter candidates do not easily explain the DAMA and CoGeNT signals, it is reasonable to consider more general frameworks. Here we consider flavor isospin-violating dark matter (IVDM) with one extra parameter, the ratio of neutron to proton couplings f_n/f_p .

IVDM has been considered previously in general analyses [9], and also recently in studies of various interpretations of the CoGeNT results [10,11]. We focus solely on IVDM and consider for the first time the distribution of isotopes present in each detector. Previous work has neglected this distribution, which implies that dark matter may be completely decoupled from any given detector for a particular value of f_n/f_p . However, this is not true if there is more than one isotope present, as is the case in many detectors, and the viability and implications of IVDM cannot be established without considering the isotope distribution. As we will see, including the isotope distribution has remarkable consequences. For a single choice of f_n/f_p , the DAMA and CoGeNT signals are consistent with each other and with current XENON constraints. At the same time, the isotope distribution implies that XENON cannot be completely decoupled, and the IVDM scenario unambiguously predicts near future signals at XENON and other detectors, such as CRESST and COUPP. We identify and discuss slight inconsistencies with other data, and present a general analysis of when experiments may be reconciled by isospin violation. Finally, we provide a quark-level realization of IVDM as WIMPless dark matter [12,13] that is consistent with all collider and low-energy bounds.

* Corresponding author.

E-mail address: jlf@uci.edu (J.L. Feng).

2. Cross sections for IVDM

We focus on the SI scattering of an IVDM particle X off a nucleus A with Z protons and $A - Z$ neutrons. The event rate is

$$R = N_T n_X \int dE_R \int_{v_{\min}}^{v_{\max}} d^3v f(v) v \frac{d\sigma}{dE_R}, \quad (1)$$

where N_T is the number of target nuclei, n_X is the local number density of dark matter particles, and the limits of the recoil energy E_R integral are determined by experimental considerations.

The IVDM particle's velocity v varies from $v_{\min} = \sqrt{m_A E_R / 2\mu_A^2}$, where $\mu_A = m_A m_X / (m_A + m_X)$, to v_{\max} , a function of the halo escape velocity, and $f(v)$ is the distribution of X velocities relative to the detector. The differential cross section is $d\sigma/dE_R = \hat{\sigma}_A m_A / (2v^2 \mu_A^2)$, with

$$\hat{\sigma}_A = \frac{\mu_A^2}{M_*^4} [f_p Z F_A^p(E_R) + f_n (A - Z) F_A^n(E_R)]^2, \quad (2)$$

where $f_{p,n}$ are the couplings to protons and neutrons, normalized by the choice of mass scale M_* , and $F_A^{p,n}(E_R)$ are the proton and neutron form factors for nucleus A .

$F_A^p(E_R)$ and $F_A^n(E_R)$ are not identical. $F_A^p(E_R)$ is what has typically been measured, but $F_A^n(E_R)$ may also be probed, for example, through neutrino and electron parity-violating scattering off nuclei [14]. However, since the isospin violation from this effect is small compared to the potentially large effects of varying f_n/f_p , we will set both form factors equal to $F_A(E_R)$. With this approximation, the event rate simplifies to $R = \sigma_A I_A$, where

$$\sigma_A = \frac{\mu_A^2}{M_*^4} [f_p Z + f_n (A - Z)]^2, \quad (3)$$

$$I_A = N_T n_X \int dE_R \int_{v_{\min}}^{v_{\max}} d^3v f(v) \frac{m_A}{2v\mu_A^2} F_A^2(E_R), \quad (4)$$

and σ_A is the zero-momentum-transfer SI cross section from particle physics, and I_A depends on experimental, astrophysical, and nuclear physics inputs. If $f_n = f_p$, we recover the well-known relation $R \propto A^2$. For IVDM, however, the scattering amplitudes for protons and neutrons may interfere destructively, with complete destructive interference for $f_n/f_p = -Z/(A - Z)$.

We assume that each detector either has only one element, or that the recoil spectrum allows one to distinguish one element as the dominant scatterer. But it is crucial to include the possibility of multiple isotopes. The event rate is then $R = \sum_i \eta_i \sigma_{A_i} I_{A_i}$, where the sum is over isotopes A_i with fractional number abundance η_i .

3. IVDM and current data

It will be convenient to define two nucleon cross sections. The first is $\sigma_p = \mu_p^2 f_p^2 / M_*^4$, the X -proton cross section. In terms of σ_p ,

$$R = \sigma_p \sum_i \eta_i \frac{\mu_{A_i}^2}{\mu_p^2} I_{A_i} [Z + (A_i - Z) f_n / f_p]^2. \quad (5)$$

The second is σ_N^Z , the typically-derived X -nucleon cross section from scattering off nuclei with atomic number Z , assuming isospin conservation and the isotope abundances found in nature. With the simplification that the I_{A_i} vary only mildly for different i , we find

$$\frac{\sigma_p}{\sigma_N^Z} = \frac{\sum_i \eta_i \mu_{A_i}^2 A_i^2}{\sum_i \eta_i \mu_{A_i}^2 [Z + (A_i - Z) f_n / f_p]^2} \equiv F_Z. \quad (6)$$

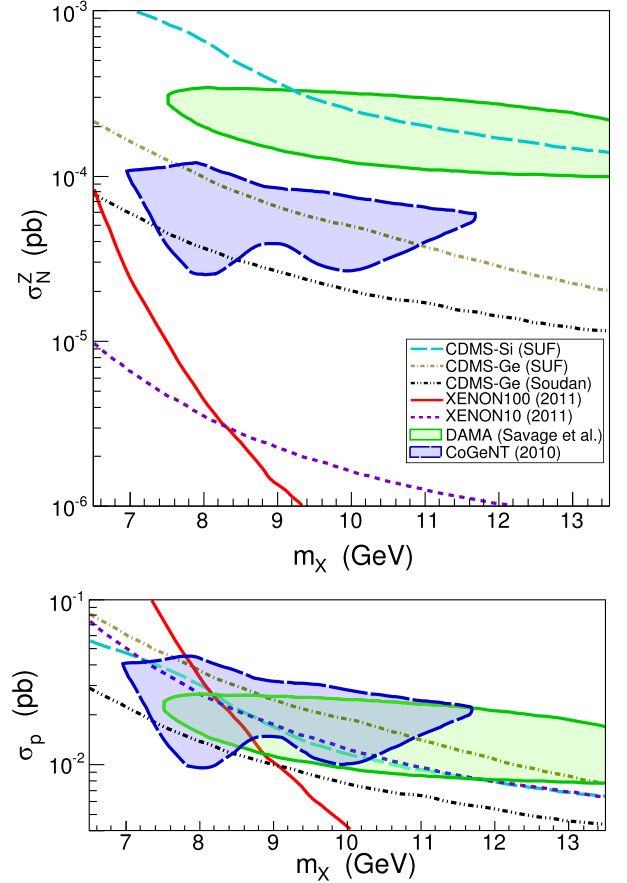


Fig. 1. Favored regions and exclusion contours in the (m_X, σ_N^Z) plane (top), and in the (m_X, σ_p) plane for IVDM with $f_n/f_p = -0.7$ (bottom).

If one isotope dominates, the well-known result, $F_Z = [Z/A + (1 - Z/A) f_n/f_p]^{-2}$, is obtained.

In Fig. 1 we show regions in the (m_X, σ_N^Z) plane and the (m_X, σ_p) plane for $f_n/f_p = -0.7$ that are favored and excluded by current bounds. These include the DAMA 3σ favored region [15, 16], assuming no channeling [17] and that the signal arises entirely from Na scattering; the CoGeNT 90% CL favored region [2]; 90% CL exclusion contours from XENON100 [3] and XENON10 [4]; and 90% CL bounds from CDMS Ge and Si [5,6]. The isotope abundances are given in Tables 1 and 2.

There are controversies regarding the exclusion contours for xenon-based detectors at low mass [18]. The energy dependence of the scintillation efficiency at low energies is uncertain, and there are questions about the assumption of Poisson fluctuations in the expected photoelectron count for light dark matter. We have also not accounted for uncertainties in the associated quenching factors for Na, Ge and Si [19]. These issues can enlarge some of the signal regions or alter some of the exclusion curves of Fig. 1. We have also not adjusted the favored regions and bounds to account for differences in the dark matter velocity distributions adopted by the various analyses, which would slightly shift the contours.

Remarkably, for $-0.72 \lesssim f_n/f_p \lesssim -0.66$, the DAMA- and CoGeNT-favored regions overlap and the sensitivity of XENON is sufficiently reduced to be consistent with these signals, since this choice of f_n/f_p leads to nearly complete destructive interference for the proton/neutron content of xenon isotopes. The possibility of IVDM therefore brings much of the world's data into agreement and leads to a very different picture than that implied by studies assuming isospin conservation. The CDMS Ge constraint marginally

Table 1
 $R_{\max}[Z_1, Z_2]$, where the Z_1 (Z_2) elements are listed in rows (columns). Elements with one significant isotope have their (Z, A) listed; those with more than one are denoted by asterisks and listed in Table 2.

Element	Xe	Ge	Si	Ca	W	Ne	C
Xe (54, *)	1.00	8.79	149.55	138.21	10.91	34.31	387.66
Ge (32, *)	22.43	1.00	68.35	63.14	130.45	15.53	176.47
Si (14, *)	172.27	30.77	1.00	1.06	757.44	1.06	2.67
Ca (20, *)	173.60	31.53	1.17	1.00	782.49	1.10	2.81
W (74, *)	2.98	13.88	177.46	166.15	1.00	41.64	466.75
Ne (10, *)	163.65	28.91	4.39	4.09	726.09	1.00	11.52
C (6, *)	176.35	32.13	1.07	1.02	789.59	1.12	1.00
I (53, 127)	1.94	5.51	127.04	118.35	20.68	28.92	326.95
Cs (55, 133)	1.16	7.15	139.65	127.61	12.32	31.88	355.27
O (8, 16)	178.49	32.13	1.08	1.03	789.90	1.13	1.01
Na (11, 23)	101.68	13.77	8.45	8.33	481.03	2.27	22.68
Ar (18, 36)	178.49	32.13	1.08	1.03	789.90	1.13	1.01
F (9, 19)	89.39	10.88	12.44	11.90	425.93	3.05	33.47

Table 2
 A_i for isotopes and their fractional number abundances η_i in percent for all isotopes with $\eta_i > 1\%$.

Xe	Ge	Si	Ca	W	Ne	C
128 (1.9)	70 (21)	28 (92)	40 (97)	182 (27)	20 (91)	12 (99)
129 (26)	72 (28)	29 (4.7)	44 (2.1)	183 (14)	22 (9.3)	13 (1.1)
130 (4.1)	73 (7.7)	30 (3.1)		184 (31)		
131 (21)	74 (36)			186 (28)		
132 (27)	76 (7.4)					
134 (10)						
136 (8.9)						

excludes the overlapping region, and since CoGeNT utilizes Ge, the tension between CoGeNT and CDMS Ge cannot be alleviated by isospin violation. However, it is possible that an improved understanding of CoGeNT backgrounds and the energy scale calibration of the CDMS Ge detectors at low energy may resolve the disagreement [6,19,20].

4. Predictions

Further tests of the IVDM hypothesis may come from other detectors. If two experiments report signals suggesting the same m_χ , their results imply an experimental measurement of

$$R[Z_1, Z_2] \equiv \sigma_N^{Z_1} / \sigma_N^{Z_2}. \quad (7)$$

$R[Z_1, Z_2] = F_{Z_2} / F_{Z_1}$ is then a quadratic equation in f_n / f_p , the solution of which enables unambiguous signal predictions for other detectors.

As timely examples, consider two current experiments. Preliminary results from CRESST may indicate a signal from scattering off oxygen [21]. $f_n / f_p \approx -0.7$ implies $F_{Z=8} \approx 44$. The IVDM explanation of DAMA and CoGeNT therefore predicts that CRESST will see a signal consistent with $m_\chi \sim 10$ GeV and $\sigma_N^{Z=8} \sim 8.5\sigma_N^{Z=32}$. Such a cross section may in fact be consistent with CRESST data [19,22]. COUPP is a CF₃I detector; its sensitivity to low-mass dark matter arises from C and F scattering. For $f_n / f_p \approx -0.7$, $m_\chi \sim 10$ GeV, we find $\sigma_N^{Z=6} \sim 8.4\sigma_N^{Z=32}$ and $\sigma_N^{Z=9} \sim 4.2\sigma_N^{Z=32}$. COUPP would be expected to report a normalized cross section between these values, with the value depending on the relative detection power of the C and F targets.

5. Relative detection prospects

Although XENON excludes CoGeNT and DAMA signals assuming isospin conservation, this is not the case for IVDM. One might then ask: given any signal at a detector with atomic number Z_1 , what sensitivity is required for a detector with atomic number Z_2

to either corroborate or disfavor this signal, allowing for isospin violation? Maximizing $R[Z_1, Z_2]$ with respect to f_n / f_p determines the factor by which the Z_2 detector must exclude the Z_1 signal assuming isospin conservation, such that the Z_1 signal is excluded even allowing for isospin violation. Similarly, maximizing $R[Z_2, Z_1]$ determines the factor by which the Z_2 detector may come up short in probing an isospin-conserving origin for the Z_1 signal, while still having the potential to find evidence for an isospin-violating origin.

In Table 1, we present $R_{\max}[Z_1, Z_2]$, the maximal value of $R[Z_1, Z_2]$ for all possible values of f_n / f_p , for many materials that are commonly used in dark matter detectors. The isotope composition of elements plays an important role in determining $R_{\max}[Z_1, Z_2]$. If the element Z_2 is composed entirely of one isotope, then it is always possible to choose f_n / f_p so that $\sigma_{Z_2} = 0$ and thus $R_{\max}[Z_1 \neq Z_2, Z_2] = \infty$; these columns have been omitted from Table 1. However, if there is more than one significant isotope, it is impossible to achieve exact destructive interference for all isotopes simultaneously, and so $R_{\max}[Z_1 \neq Z_2, Z_2]$ is finite. In particular, although isospin violation can weaken the bounds achieved by Xe and Ge detectors, we see in Table 1 that these bounds can be weakened by at most two orders of magnitude. Upcoming XENON results may therefore exclude DAMA and CoGeNT, even for IVDM; XENON bounds already eliminate some of the DAMA/CoGeNT overlap region (Fig. 1), and will probe the entire region if XENON sensitivities are improved by an order of magnitude.

6. Isospin violation in WIMPlless models

So far we have worked at the nucleon level. We now provide a quark-level theory of dark matter that generically realizes isospin violation. In supersymmetric WIMPlless dark matter models [12, 13], dark matter particles X freeze out in a hidden sector with the correct relic density and interact with the standard model through connector particles Y . We consider the superpotential

$$W = \sum_i (\lambda_q^i X Y_{q_L}^i q_L^i + \lambda_u^i X Y_{u_R}^i u_R^i + \lambda_d^i X Y_{d_R}^i d_R^i), \quad (8)$$

where X is a real scalar dark matter particle, q_L, u_R, d_R are standard model quarks, i labels generations, and the connectors Y_{q_L, u_R, d_R} are 4th generation mirror quarks. Assuming real Yukawa couplings and $m_Y = m_{Y_{u,d}} \gg m_\chi, m_q$, the connector particles induce the SI operators

$$\mathcal{O}_i = \lambda_q^i \lambda_u^i X X \bar{u}^i u^i / m_Y + \lambda_q^i \lambda_d^i X X \bar{d}^i d^i / m_Y, \quad (9)$$

leading to the scattering cross section of Eq. (3) with $f_{p,n}/M_*^2 = \sum_i (\lambda_q^i \lambda_u^i B_{ui}^{p,n} + \lambda_q^i \lambda_d^i B_{di}^{p,n}) / (\sqrt{\pi} m_\chi m_Y)$. The $B_{qi}^{p,n}$ are integrated nuclear form factors, including $B_u^p = B_d^n \approx 6$, $B_u^n = B_d^p \approx 4$ [7].

The amount of isospin violation in dark matter–nucleus interactions is solely determined by the Yukawa flavor structure. There are many possibilities; WIMPlless models may explain the DAMA signal with couplings to either the 1st [12] or 3rd [13,23] generation. Here we assume only 1st generation quark couplings, automatically satisfying flavor constraints. Assuming $m_\chi = 10$ GeV and $m_Y = 400$ GeV, consistent with all collider and precision electroweak bounds, the region of the $(\lambda_q^1 \lambda_u^1, \lambda_q^1 \lambda_d^1)$ plane that explains DAMA and CoGeNT is

$$\lambda_u^1 \simeq -1.08 \lambda_d^1, \quad 0.013 \lesssim \lambda_q^1 \lambda_d^1 \lesssim 0.024. \quad (10)$$

IVDM is clearly generic in this microscopic model of dark matter interactions and may simultaneously reconcile the DAMA and CoGeNT signals and XENON bounds.

The IVDM reconciliation of DAMA, CoGeNT, and XENON relies on cancellations between p and n couplings, and so requires larger couplings than in the isospin-preserving case to maintain the desired DAMA and CoGeNT signals. Such models may potentially violate collider constraints, which are not subject to cancellations. This WIMPlless model provides a quark-level framework in which one may investigate this question.

The most stringent model-independent constraints are from Tevatron searches for $p\bar{p} \rightarrow XX + \text{jet}$ [24,25]. Using MadGraph/MadEvent 4.4.32 [26], one can compute the monojet cross section (requiring jet $E_T > 80$ GeV) induced by the operator of Eq. (9). The resulting 2σ bounds from Tevatron data are roughly $\lambda_q^1 \lambda_{u,d}^1 \lesssim 1$, two orders of magnitude too weak to probe the DAMA and CoGeNT favored couplings described in Eq. (10).

7. Conclusions

Results for spin-independent dark matter interactions typically assume identical couplings to protons and neutrons. Isospin violation is generic, however, and we have shown that IVDM with $f_n/f_p \approx -0.7$ may explain both DAMA and CoGeNT, consistent with XENON10/100 bounds. This scenario is only marginally excluded by CDMS Ge constraints, unambiguously predicts a signal at CRESST, and may even be tested by XENON, given its several significant isotopes, as discussed above; near future data will shed light on this picture. More generally, we have explored the extent to which dropping the $f_p = f_n$ assumption may reconcile results from various detectors, stressing the important role played by the distribution of isotopes. Finally, we have shown that IVDM is easily realized in a quark-level model consistent with all low-energy and collider observables.

Note added in proof

After the completion of this work, an annual modulation signal from CoGeNT and a new constraint from SIMPLE have been reported. These results and some of the following discussion may be found in Refs. [27,28].

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