Probing Isospin-Violating Dark Matter

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We discuss experimental probes of isospin-violating dark matter (IVDM), including direct and indirect detection strategies. We point out the important role which IVDM plays in understanding recent data regarding low-mass dark matter, and describe strategies for finding evidence of IVDM at current and upcoming experiments.

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1. Introduction

Dark matter search strategies at direct detection experiments are typically based on several nominal assumptions. Among these assumptions are

- that dark matter has a Maxwellian velocity distribution, and a density $\sim 0.3$ GeV/cm$^3$ near the earth.
- that dark matter scatters elastically off nuclei.
- that dark matter interacts with Standard Model matter through effective contact operators (equivalently, the mediating particles are heavy).
- that dark matter interactions are isospin-invariant (that is, that dark matter interacts with protons and neutrons in the same way).

One must keep in mind that any deviation from these assumptions can modify the comparison of experimental results from different experiments.

In these proceedings, we focus on the last assumption: isospin-invariant interactions. The main motivation for this assumption is the fact that, in most models where the dark matter is the lightest neutralino of the MSSM, dark matter interactions are indeed largely isospin-invariant. However, this motivation loses force as soon as one considers models beyond LSP WIMPs.

Isospin-violating dark matter (IVDM) can have an important impact on the interpretation of data. This is especially relevant when considering low-mass dark matter ($m_X \sim 5 - 20$ GeV). DAMA, CoGeNT, and CRESST have reported data consistent with low-mass dark matter, though not necessarily consistent with
each other. However, CDMS\cite{cdms}, XENON10/100\cite{xenon}, and SIMPLE\cite{simple} have reported data which is in tension with this interpretation. Issues have been raised regarding the credibility of all these experimental results, and we will not delve into these issues any further. Instead, we will focus on the fact that the tension between these data sets has been found under the assumption of isospin-invariant interactions; this situation changes significantly for IVDM. We will see that neutrino-based indirect detection searches have an interesting complementary role in probing IVDM.

2. Isospin-Violating Dark Matter

For simplicity, we assume dark matter scatters elastically with Standard Model nuclei through contact interactions. In this case, the rate at which dark matter-nucleus scattering occurs can be written as

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

where $N_T$ is the number of target nuclei, $n_X$ is the dark matter number density near the earth, $\sigma$ is the dark matter-nucleus scattering cross-section and $E_R$ is the nuclear recoil energy. $f(v)$ is the dark matter velocity distribution and $v_{\text{min}} = \sqrt{m_A E_R / 2 \mu^2_A}$ is the minimum dark matter velocity for which it is kinematically possible to produce a recoil energy $E_R$. The dark matter-nucleus reduced mass is $\mu_A = m_A m_X / (m_A + m_X)$. $v_{\text{max}}$ is determined by the galactic escape velocity, and the $E_R$ integration limits are determined by the thresholds of the experiment.

The differential cross-section can be written as

$$ \frac{d\sigma}{dE_R} = \frac{m_A}{2 v^2 \mu^2_A} \hat{\sigma}_A, \quad (2) $$

where

$$ \hat{\sigma}_A = \frac{\mu^2_A}{M_*^2} \left[ f_p Z F_A^p(E_R) + f_n (A - Z) F_A^n(E_R) \right]^2. \quad (3) $$

$M_*$ is an overall energy scale, $f_{p,n}$ are the dark matter couplings to protons and neutrons, and $F_A^{p,n}(E_R)$ are nuclear form factors. Isospin-invariant interactions imply $f_n = f_p$. The nuclear form factors for protons and neutrons are not the same, and thus are an additional source for isospin-violating interactions. However, as this effect is relatively small compared to the effect of $f_n \neq f_p$, will assume (for simplicity) $F_A^p(E_R) \sim F_A^n(E_R) = F_A(E_R)$. We can then write $R = \sigma_A I_A$, where

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

$$ I_A = N_T n_X \int dE_R \int_{v_{\text{min}}}^{v_{\text{max}}} d^3 v f(v) \frac{m_A}{2 v \mu^2_A} F_A^2(E_R). \quad (5) $$

$I_A$ encodes the nuclear and astrophysics, while $\sigma_A$ encodes the dark matter particle physics; it is the latter factor we will focus on.
The cross-section for dark matter to scatter off a single proton, $\sigma_{SI}^p$, is then
\[
\sigma_{SI}^p = \frac{\mu_p^2 f_p^2}{M_N^4},
\] (6)
in terms of which the event rate can be written as
\[
R = \sigma_{SI}^p \sum_i \eta_i \frac{\mu_{A_i}^2}{\mu_p^2} I_{A_i} [Z + (A_i - Z)f_n/f_p]^2.
\] (7)
This allows one to relate an observed event rate to $\sigma_{SI}^p$ for a given value of $f_n/f_p$.

Here, $\eta_i$ is the natural abundance of each isotope $i$, with atomic mass $m_{A_i}$.

Dark matter signal and exclusion regions are typically expressed in terms of $\sigma_{SI}^Z$, the normalized dark matter-nucleon scattering cross-section. $\sigma_{SI}^Z$ can be determined from the rate above by setting $f_n = f_p$, and is related to $\sigma_{SI}^p$ by
\[
F_Z \equiv \frac{\sigma_{SI}^p}{\sigma_{SI}^Z} = \sum_i \eta_i \frac{\mu_{A_i}^2}{\mu_p^2} [Z + (A_i - Z)f_n/f_p]^2.
\] (8)
$F_Z$ depends only on known atomic physics, and on $f_n/f_p$. If $f_n \neq f_p$, the dark matter-nucleon scattering cross-section is not really a sensible physical quantity. $F_Z$ represents the factor by which the normalized-to-nucleon cross-section reported by an experiment (assuming isospin-invariant interactions) must be scaled to obtain the physical cross-section for dark matter scattering off a proton.

3. Low-mass dark matter

We now apply this analysis to the low-mass dark matter data. In fig. 1 (see ref. 3), we plot signal regions for DAMA$^{14}$ ($3\sigma$), CoGeNT$^6$ (90% CL) and CRESST$^7$ ($2\sigma$), as well as 90% CL exclusion contours for CDMS$^8$, XENON10$^{10}$, XENON100$^{11}$ and SIMPLE$^{13}$. The left panel assumes $f_n/f_p = 1$, while the right panel assumes $f_n/f_p = -0.7$. This latter value yields the maximum suppression possible for the dark matter-xenon scattering cross-section due to interference between protons and neutrons. Isospin-violating interactions have a dramatic effect on the consistency of data sets from different experiments$^{12,15}$. For $f_n/f_p \sim -0.7$, the DAMA and CoGeNT signal regions are consistent ($m_X \sim 8$ GeV, $\sigma_{SI}^p \sim 3 \times 10^{-2}$ pb) and satisfy bounds from xenon-based experiments, which are the most constraining bounds for isospin-invariant interactions.

On the other hand, IVDM may not provide a complete reconciliation of all the data$^{12,15}$. There is marginal tension between the exclusion contour of CDMS (Soudan) and the signal region of CoGeNT; this cannot be alleviated by isospin-violating interactions, as both data sets use germanium detectors. Moreover, the bounds from SIMPLE are more constraining on models which can match the CoGeNT data if $f_n/f_p \sim -0.7$. Even the signal regions cannot be brought into perfect alignment; the choice of $f_n/f_p$ which reconciles the DAMA and CoGeNT data does not reconcile the CRESST data.
The experimental situation may change significantly in the near future. CoGeNT has indicated that their experiment may have more surface area contamination than previously thought. Preliminary indications are that this would move their signal region to larger mass and smaller $\sigma_p^{SI}$, bringing it more in line with CRESST. Understanding of xenon’s response to low-energy recoils is steadily improving. Many experimental uncertainties may be clarified with more data.

More of the data may be brought into alignment if, in addition to isospin-violating interactions, one weakens other assumptions by allowing low-mass mediated interactions, inelastic scattering, and/or non-Maxwellian velocity distributions. It is clear, however, that isospin-violating interactions can have a large effect on the understanding of the low-mass data, and must be taken into account.

4. New Experiments

For $f_n/f_p \sim -0.7$, the sensitivity of CRESST and SIMPLE increased relative to CoGeNT. This is because they have a carbon, oxygen and fluorine target nuclei, for which the neutron-to-proton ratio is smaller than that of germanium. Several other experiments with similar targets can test these low-mass IVDM models. These include COUPP, DMTPC, and the Directional Dark matter Detector ($D^3$), whose prototype is in the commissioning phase at the University of Hawaii. One can parameterize the sensitivities they can achieve for $f_n/f_p \sim -0.7$ by computing the ratio of the normalized-to-nucleon cross-section inferred from these target nuclei to that inferred from germanium:

$$\sigma_N^{Z=C} \sim 8.4 \times \sigma_N^{Z=Ge},$$
$$\sigma_N^{Z=O} \sim 8.5 \times \sigma_N^{Z=Ge},$$
$$\sigma_N^{Z=F} \sim 4.2 \times \sigma_N^{Z=Ge}.$$  (9)
Given the confusing experimental situation regarding direct detection data, it is worthwhile to consider alternative tests of IVDM. An interesting method utilizes neutrino detectors, which search for the flux of neutrinos arising from dark matter annihilation in the core of the sun. The neutrino flux is determined by the dark matter annihilation rate. Assuming that the sun is in equilibrium, the dark matter annihilation rate is half of the capture rate, which is largely determined by $\sigma_{SI}$. The sun contains many low-neutron targets which are less susceptible to destructive interference between proton and neutron couplings (for hydrogen, there is no destructive interference). Super-Kamiokande is capable of providing competitive sensitivity to low-mass dark matter, and its sensitivity to IVDM allows it to probe models which could match the low-mass data.

Liquid scintillation neutrino detectors, such as KamLAND can also be sensitive to IVDM models. In this analysis, one must rely on the ability to reconstruct the track of the lepton produced in a charged-current interaction from the timing of when the first scintillation photons reach the photomultiplier tubes. This reconstruction can allow one to determine the direction and energy of a fully-contained charged lepton, allowing one to determine if the initial neutrino came from the direction of the sun. Moreover, it permits lepton flavor discrimination, which is useful for selecting events produced by electron neutrinos. An analysis using electron neutrinos has the advantage of a much smaller atmospheric neutrino background. Also, the quick attenuation of the electron shower allows one to measure the full energy of the charged lepton. Assuming the energy and angular resolutions found in Ref. 26, we plot in fig. 2 (see ref. 25) the sensitivity of a 1 kT LS detector operating for 2135 live-days and assuming $f_n/f_p = 1, -0.7$. Also plotted for reference are the signal regions of CoGeNT and DAMA and exclusion contours from CDMS and XENON10/100. KamLAND can potentially be sensitive to IVDM models (with $f_n/f_p \sim -0.7$) which could match the low-mass data.
5. Matching Multiple Experiments

Moving beyond the low-mass data, there are two basic questions one can ask:

- Given a signal at one detector, what is the minimum exposure a different detector might need to confirm it, allowing for IVDM?
- Given a signal at one detector, what is the maximum exposure a different detector would need to definitely contradict it, even allowing for IVDM?

We can answer this by determining the sensitivity to $\sigma_Z^N$, the normalized-to-nucleon cross-section assuming isospin-invariant interactions, a second experiment would need to either possibly confirm or definitely refute a signal from the first experiment. These are given by the maximum and minimum (with respect to $f_n/f_p$) of the ratio

$$R[Z_1, Z_2](f_n/f_p) = \frac{\sigma_{Z_1}^N}{\sigma_{Z_2}^N} = \frac{F_{Z_2}}{F_{Z_1}}.$$  \hspace{1cm} (10)

The isotope content plays a key role in this analysis. For an element $Z$ with only one isotope, the quantity $R_{\text{max}}[Z_1, Z]$ is infinite, allowing an IVDM model with $f_n/f_p = Z/(Z - A)$ to evade the bounds from a $Z$-based detector. This is not the case if there are multiple isotopes with a non-negligible abundance; no choice of $f_n/f_p$ can cancel the response from all isotopes. For an IVDM signal at a Ge-based detector to be definitively probed by a Xe-based detector, the latter must have at most a factor of $\sim 22$ greater sensitivity than the former. Considering the great sensitivity of large Xe-based detectors, IVDM models matching the low-mass data of CoGeNT, DAMA and CRESST can eventually be probed at xenon detectors.

6. IceCube/DeepCore

We have seen that the sensitivity of neutrino detectors to IVDM can be significantly enhanced. For large $m_X$, IceCube/DeepCore has the greatest sensitivity of all neutrino detectors. We compare its sensitivity to IVDM to that of other current and future direct detection experiments, for a range of masses and values of $f_n/f_p$.\(^{27}\)

The sensitivity of IceCube/DeepCore to IVDM is determined from its sensitivity to the spin-dependent scattering cross-section\(^{28}\) scaled by the ratio of capture rate for IVDM to that for purely spin-dependent scattering. The capture rate for IVDM can be computed for any choice of $f_n/f_p$ by correctly accounting for the cross-section for scattering off any element in the sun. These bounds are shown in fig. 3 (see ref.\(^ {27}\), along with expected sensitivities from XENON1T\(^ {29}\) SuperCDMS (100 kg target mass)\(^ {30}\) MiniCLEAN, DEAP-3600, and CLEAN (neon or depleted argon)\(^ {31}\).

We see that for $f_n/f_p \sim -0.7$, IceCube/DeepCore can, with 180 days of data, have sensitivity exceeding all current detectors for $m_X > 50$ GeV, and even rivals the sensitivity achievable with XENON1T\(^ {27}\) Similarly, for $f_n/f_p \sim -0.82$, a value for which the sensitivity of argon detectors is maximally suppressed, IceCube/DeepCore's sensitivity would exceed MiniCLEAN and DEAP-3600, and would be comparable to that of CLEAN (with an argon target).
7. Conclusions

With exciting potential evidence for dark matter arising from DAMA, CoGeNT and CRESST, along with improving exclusion bounds from experiments like XENON100, there is a renewed focus on detailed comparison of results from different detectors. Most often, this comparison is made under the assumption that dark matter interactions are isospin-invariant. Relaxation of this assumption can have dramatic effects on the consistency (or tension) between different data sets.

In particular, IVDM can relieve the tension between the exclusion contours of xenon-based experiments, and signal regions of other experiments. But the fortuitous presence of many xenon isotopes with significant abundance ensures that xenon-based experiments will, with more data, be able to probe IVDM models which could match the low-mass data.

Several experiments with low-neutron targets, such as COUPP, may soon provide sensitivities to IVDM complementary to that available to xenon-based experiments. Neutrino-based indirect searches at Super-Kamiokande and KamLAND can potentially probe low-mass IVDM with data already taken. For higher mass dark matter, IceCube/DeepCore will, with 180 days of data, have a sensitivity to some regions of IVDM parameter-space which exceeds all current detectors, and is comparable even to many planned experiments.

A variety of new data will soon come from different detectors, and IVDM may be an important piece in interpreting this data. Models of IVDM can be constrained by gamma-ray and collider searches, and new data will provide further tests.

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