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Spin-dependent WIMPs in DAMA?

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Abstract: We investigate whether the annual modulation observed in the Dama experiment can be due to a weakly-interacting massive particle (WIMP) with an axial-vector (spin-dependent; SD) coupling to nuclei. We evaluate the SD WIMP-proton cross section under the assumption that such scattering accounts for the Dama modulation, and we do the same for a SD WIMP-neutron cross section. We show that SD WIMP-proton scattering is ruled out in a model-independent fashion by null searches for energetic neutrinos from WIMP annihilation in the Sun, and that SD WIMP-neutron scattering is ruled out for WIMP masses $\gtrsim 20\,\mathrm{GeV}$ by the null result with the Dama Xe detector. A SD WIMP with mass $\lesssim 20\,\mathrm{GeV}$ is still compatible, but only if the SD WIMP-neutron interaction is four orders of magnitude greater than the WIMP-proton interaction.

Keywords: Dark Matter, Supersymmetric Standard Model.

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Contents

1. Introduction

Weakly-interacting massive particles (WIMPs) have long been sought experimentally as the primary component of the dark halo that enshrouds the Milky Way [1]. Such dark-matter particles could be detected directly via observation of the $\mathcal{O}(10\,\mathrm{keV})$ nuclear recoils they would produce in a low-background detector when a dark-matter particle scatters elastically from a nucleus therein [2, 3]. They could also be detected indirectly via observation of the energetic neutrinos produced by annihilation of WIMPs that have accumulated in the Sun and/or Earth [4].

The WIMP can scatter elastically from a nucleus either via a scalar (spin-independent; SI) interaction, in which case the WIMP-nucleus cross section scales with the mass of the nucleus (see, e.g. ref. [1, figure 26]), or via an axial-vector (spin-dependent; SD) interaction, in which case the cross section is non zero only if the nucleus has a non-vanishing spin. In this latter case, WIMP-nucleus scattering occurs primarily via interaction of the WIMP with the unpaired proton or neutron, and therefore the WIMP-nucleus cross section will mostly depend on the SD WIMP-proton interaction in odd-Z nuclei and on the SD WIMP-neutron interaction in odd-N nuclei.

The Dama collaboration [5] has reported an annual modulation in their NaI detector compatible with the summer-winter variation in the flux of WIMPs incident on the detector due to the motion of the Earth through the halo [3]. If interpreted as a WIMP with SI interactions, the effect singles out a region in the plane (WIMP mass, WIMP-nucleon cross section), centered at about ($50\,\mathrm{GeV}$, $7\times10^{-6}\,\mathrm{pb}$), which is largely excluded by the null result reported by the Cdms collaboration using a detector made of natural germanium [6]. Further data from more sensitive detectors will allow a firmer statement on this contradiction.

An alternative explanation is that the WIMP has a dominantly SD coupling with nuclei. In this case, the incompatibility between the DAMA and CDMS results disappears as Na and I are unpaired-proton nuclei, while natural germanium contains only $\sim 8\%$ of the ^{73}Ge isotope which is an unpaired-neutron nucleus. Thus, it is conceivable that a WIMP could undergo a SD interaction in one detector while remaining invisible to the other. Such an explanation has been neglected since the required WIMP SD cross sections exceed those expected in currently favored supersymmetric models. However, given the number of free parameters in the minimal supersymmetric extension of the standard model (MSSM), not to mention the numerous possible alternatives, a WIMP with a strong SD coupling to nuclei is certainly plausible.

Here we show that this possibility can be rejected experimentally (except for a small unusual corner of parameter space), rather than through theoretical prejudice. WIMPs with SD couplings to protons will be captured in the Sun and annihilate therein producing energetic neutrinos that should be detectable in several existing neutrino telescopes. Following a model-independent approach [7, 8], we show that current upper limits to the neutrino flux rule out the possibility that the DAMA signal is due to a WIMP with SD couplings to protons. We check also that the alternative hypothesis — that the modulation signal is due to SD scattering from neutrons in Na and I — is, excluded for WIMP masses $M_\chi \gtrsim 20\,\mathrm{GeV}$ by null searches with odd-neutron targets (the best limit comes from an experiment with enriched liquid Xe performed by the DAMA collaboration as well [9]).

Indirect-detection rates have already been calculated for a variety of supersymmetric models that fit the DAMA modulation signal (see ref. [10] and references therein). Here, however, we carry out a model-independent analysis that does not rely on any details of the particle-physics model.

Below we first discuss the procedure to derive the region in the plane (WIMP mass, WIMP-nucleon cross section) compatible with the DAMA modulation signal both for SI and SD interactions. We then review the model-independent constraints from ref. [7] to this parameter space in case of SD interactions with protons. We then show that the null result with Xe strongly constrains the possibility that the DAMA modulation could be due to a WIMP SD interactions with neutrons. We then make some closing remarks.

2. Analysis of the modulation signal

DAMA has analyzed the measured modulation assuming it is due to WIMPs with SI couplings only, publishing the corresponding compatible region of WIMP masses and cross sections. The analysis for WIMPs with SD interactions is completely analogous. We now detail the calculation.

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The differential direct-detection rate (per unit detector mass) in a detector made of nucleus i is

$$\frac{dR_i}{dQ} = \frac{\rho_\chi}{M_\chi\, M_i} \int_{|\vec{v'}|\geq v_{\min}} d^3\vec{v'}\ f(\vec{v'})\,|\vec{v'}|\,\frac{d\sigma_{\chi i}}{dQ}\,, \tag{2.1}$$

where Q is the energy deposited in the detector, and $d\sigma_{\chi i}/dQ$ is the differential cross section for WIMP elastic scattering with the target nucleus. We assume here that WIMPs of mass M_χ account for a local dark-matter density ρ_χ and have a local (i.e. in the rest frame of the detector) distribution in velocity space f with normalization $\int d^3\vec{v'} f(\vec{v'}) = 1$.

The differential cross section is usually re-written as

$$\frac{d\sigma_{\chi i}}{dQ} = \frac{1}{Q_{\max}} \left(\sigma_{\chi i}^{\rm SI} F_i^2(Q) + \sigma_{\chi i}^{\rm SD} \frac{S_i(Q,a_p,a_n)}{S_i(0,a_p,a_n)} \right), \tag{2.2}$$

where $Q_{\max} = 2\,m_{\chi i}^2\,|\vec{v'}|^2/M_i$, and m_{ji} is the reduced mass between particles j and i. The form-factor suppression of the cross section depends on whether the interaction is SI or SD. The SI form factor $F_i(Q)$ is relatively simple to calculate; the estimate for the SD form factor $S_i(Q,a_p,a_n)$ requires more sophisticated nuclear modeling [11] and differs in case of SD WIMP-proton and SD WIMP-neutron scattering.

To compare results obtained with detectors of different materials, the cross section for WIMP scattering from nucleus i (for SI or SD) is expressed in terms of the WIMP-proton (neutron) cross section scaled to zero momentum transfer, $\sigma_{\chi i} = (m_{\chi i}^2/m_{\chi p}^2) C_{p(n)} \sigma_{p(n)}$. For SI scattering, $C_{p(n)}^{\rm SI} = [Z_i\, f_p + (A_i - Z_i)\, f_n]^2 / f_{p(n)}^2$, where A_i and Z_i are the atomic mass number and charge of nucleus i, and $f_p \simeq f_n$ are the SI couplings of WIMPs to protons and neutrons, respectively. For SD scattering, $C_{p(n)}^{SD} = 4\,(\lambda_{p(n)}^i)^2 J_i(J_i+1)/3$, where J_i is the total angular momentum of nucleus i, and $\lambda_{p(n)}^i = (a_p\langle S_p^i\rangle + a_n\langle S_n^i\rangle)/(a_{p(n)}J_i)$. Here, a_p and a_n are the WIMP SD couplings to protons and neutrons and $\langle S_p^i\rangle$ and $\langle S_n^i\rangle$ are the proton and neutron spin expectation values in nucleus i; they are obtained from nuclear models [11].

Finally, to get the differential detection rate for NaI one has to take into account the fact that this is not a monatomic material and include quenching factors for both Na and I.

Equation (2.1) is time dependent; the dependence is written implicitly in the change of variables between the velocity of the WIMP in the detector rest frame and in the galactic frame. The rotation of the Earth around the Sun gives rise to the well-known annual-modulation effect [3]. To a good approximation, the signal event rate in the kth energy bin can be parameterized by separating a component averaged during the year from a time-dependent component,

$$\mathcal{S}_k = \mathcal{S}_{0,k} + \mathcal{S}_{m,k} \cos\left[\frac{2\pi(t-t_0)}{T}\right], \tag{2.3}$$

where the period T is 1 year and t_0 is about June 2. DAMA performs a maximum-likelihood analysis and provides values of $\mathcal{S}_{0,k}$ and $\mathcal{S}_{m,k}$ corresponding to their favored region in 4 energy bins, with electron equivalent (measured) energies $Q_{\rm ee}$ between 2 and 6 keV [5].

Since we cannot perform an analysis on the raw data, we consider an approximate method to decide whether a WIMP candidate is compatible with the DAMA modulation or not. We follow ref. [12] and define the statistical variable,

$$\kappa = \sum_k \left[\frac{\left(\mathcal{S}^{\rm th}_{0,k} - \mathcal{S}^{\rm exp}_{0,k}\right)^2}{\left(\Delta\mathcal{S}^{\rm exp}_{0,k}\right)^2} + \frac{\left(\mathcal{S}^{\rm th}_{m,k} - \mathcal{S}^{\rm exp}_{m,k}\right)^2}{\left(\Delta\mathcal{S}^{\rm exp}_{m,k}\right)^2} \right], \tag{2.4}$$

where $\mathcal{S}^{\rm exp}_{0,k}$ is the experimental result and $\mathcal{S}^{\rm th}_{0,k}$ is the theoretical prediction for the WIMP candidate being investigated.

Before considering the SD case of interest to us here, we first carry out our analysis with a SI WIMP-nucleon coupling to test whether our technique reproduces the results of the full DAMA analysis that has been published for this case. To do so, we evaluate $\mathcal{S}^{\rm th}_{0,k}$ and $\mathcal{S}^{\rm th}_{m,k}$ as a function of WIMP mass and $\sigma_p^{\rm SI}$ (we assume, as DAMA did, that $f_p = f_n$; we take also their choice of form factors and astrophysical parameters). The 3σ region singled out by DAMA with their maximum-likelihood method in the $(M_\chi,\, \sigma_p^{\rm SI})$ plane is reproduced fairly well if we require that $\kappa <\ 60$.

We now turn to our analysis of a WIMP with SD interactions. We take the form factor for SD scattering from Na and I from ref. [13] and again assume that the WIMP candidate is compatible with the DAMA modulation if $\kappa < 60$. We consider separately the case of coupling with protons only ($a_p \neq 0,\, a_n = 0$) and with neutrons only ($a_p = 0,\, a_n \neq 0$); the results are indicated by the shaded regions, respectively, in figure 1 and in figure 2. (These approximate results agree to better than a factor of two with a more precise analysis of the raw data [14] released after our paper was submitted.)

3. A WIMP-proton interaction?

We examine first the case of WIMPs with couplings with protons. Such WIMPs scatter efficiently from protons in the Sun, losing enough energy to become gravitationally bound to the Sun. This process creates an enhancement in the density of WIMPs at the center of the Sun. The WIMPs can then annihilate in the Sun, and among the decay products of the annihilation products will be energetic neutrinos (energies of order half the WIMP mass) that can escape the Sun. Such neutrinos can produce upward muons via a charged-current interaction in the material below a neutrino detector, such as that at IMB, Super-Kamiokande, Baksan, MACRO, and/or AMANDA.

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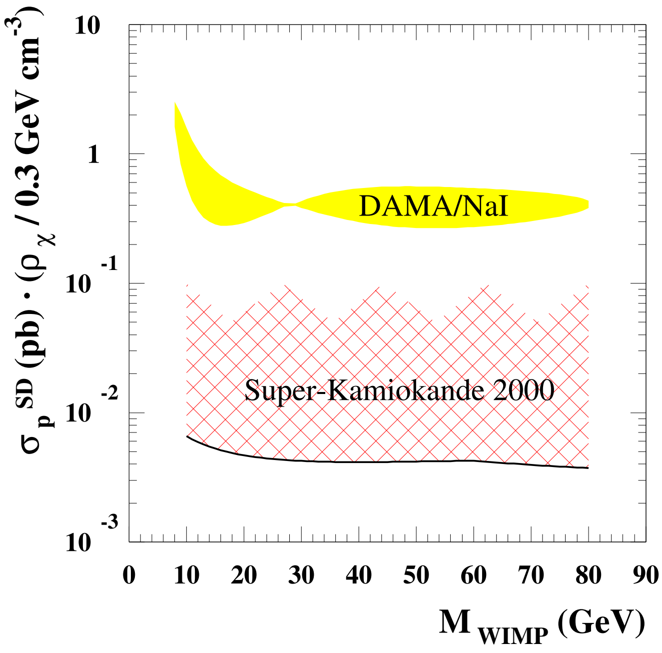

Figure 1: The shaded region shows the parameter space (in WIMP mass versus SD WIMP-proton cross section) implied by the DAMA annual modulation for a WIMP with exclusively SD interactions with protons and no interaction with neutrons. The solid curve indicates the upper bound to the SD WIMP-proton cross section from null searches for neutrino-induced upward muons from the Sun; thus the cross hatched region is excluded.

The calculation of the flux of such neutrino-induced upward muons from the Sun is straightforward. For the masses we are considering, the flux can be written [1, 7][1]

$$\begin{aligned}\Gamma = {} & 0.016\,\mathrm{m}^{-2}\mathrm{yr}^{-1}\,(M_\chi/\mathrm{GeV})(\sigma_{\chi p}^{\rm SD}/10^{-40}\,\mathrm{cm}^2)\times \\ & \times(\rho_\chi/0.3\,\mathrm{GeV\,cm}^{-3})S(m_\chi/m_H)\xi(m_\chi)\,,\end{aligned} \tag{3.1}$$

Here, $S(x)$ is given by ref. [1, eq. (9.21)]. The function $\xi(m_\chi)$ is given in ref. [1, figure 33]; it quantifies the number of neutrino-induced muons expected per annihilation event. This depends in detail on the annihilation products; e.g. $b\bar{b}$ or $c\bar{c}$ quarks, and/or $\tau^+\tau^-$ lepton pairs. Different WIMP candidates in the mass ranges we are considering ($m_\chi \lesssim 80\,\mathrm{GeV}$) will produce different branching fractions to these annihilation products, so the allowed range for $\xi(m_\chi)$ will span the range allowed by these final states. For the WIMP masses we are considering, $0.03 \lesssim \xi(m_\chi) \lesssim 0.13$; we use $\xi = 0.03$. The bound we compute here could be evaded if the WIMP annihilated primarily to $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, e^+e^-, and/or $\mu^+\mu^-$ pairs, as these final states do not produce a significant neutrino signal. However, we know of no models in which (nor any reason why) this would occur. Equation (3.1) assumes that capture of WIMPs in

[1] Note in ref. [1, eq. (9.55)], the factor $\tanh(t_\odot/\tau_\odot)$ should be squared and there should be a factor of $\xi(m_\chi)$ on the right-hand side.

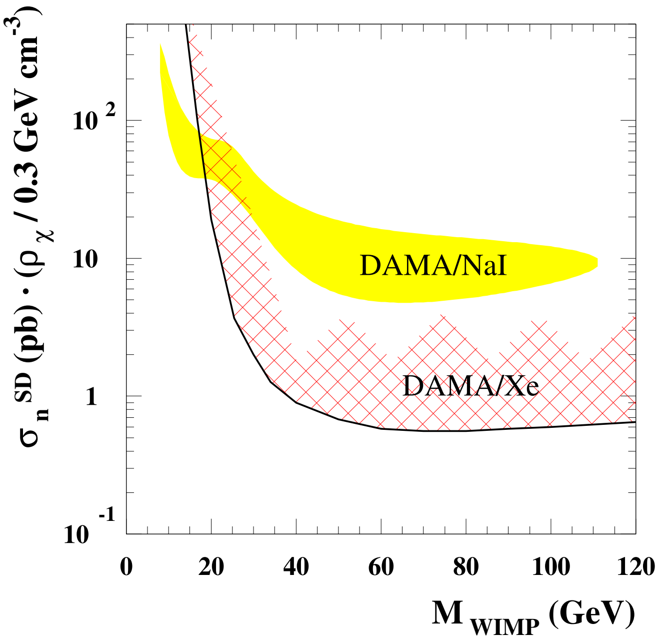

Figure 2: The shaded region shows the parameter space (in WIMP mass versus SD WIMP-neutron cross section) implied by the DAMA annual modulation under the assumption that the signal is due exclusively to SD WIMP-neutron scattering. The solid curve indicates the upper bound to the SD WIMP-neutron cross section from the DAMA Xe detector. Again the cross hatched region is excluded.

the Sun from the Galactic halo is in equilibrium with their depletion by annihilation. As argued in ref. [1], capture and annihilation will be in equilibrium in just about any model in which the signal is anywhere close to being detectable. Since we are going to place upper limits to a WIMP-proton scattering cross section based on current bounds, we may safely assume capture-annihilation equilibration in our analysis.

The upper limit to the flux of neutrino-induced muons from the Sun (roughly $\lesssim 10^{-2}\,\mathrm{m}^{-2}\,\mathrm{yr}^{-1}$) from Super-Kamiokande [15], leads to the upper limit to the cross section for WIMP-proton SD scattering shown in figure 1 (limits from Baksan, MACRO and AMANDA lead to very similar results). The discrepancy of a couple of orders of magnitude between the region disallowed by neutrino telescopes and the region implied by DAMA is much too large to be explained by the uncertainties and approximations inherent in our analysis, which might conceivably change our DAMA parameter space and/or our Super-Kamiokande limit by no more than factors of a few.

4. A WIMP-neutron interaction?

In the simplest odd-group model of the Na and I nuclei, the spin with which a SD WIMP interacts is carried exclusively by the unpaired proton. In such a model, the

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WIMP can undergo SD scattering with the nucleus only through the WIMP-proton interaction, and not through any WIMP-neutron interaction. However, in more sophisticated nuclear models, some small fraction of the spin is carried by neutrons as well. It is thus conceivable that the DAMA modulation could have been caused by a SD WIMP-neutron interaction. We now show that this possibility is disfavored by the null results of WIMP searches with odd-neutron targets.

In particular, the best current limit has been obtained from an experiment with enriched liquid Xe (99.5% ^{129}Xe) performed as well by the DAMA collaboration (we checked that a weaker limit is given by the CDMS measurement with natural Ge, with only $\sim 8\%$ of the ^{73}Ge isotope). We plot in figure 2 the limit derived in ref. [9] using again form factors from ref. [13]. More precisely, the DAMA Xe analysis derives a limit that assumes $a_n = -0.85\, a_p$. Our limit, for $a_p = 0$ and $a_n \neq 0$, is obtained from this by scaling up by a factor $1/(1 - 2/0.85\, \langle S_p \rangle / \langle S_n \rangle) \sim 1.22$. The uncertainty in this scaling, $\mathcal{O}(20\%)$, is negligible for our purposes.

If the WIMP has SD interactions with the proton and neutron in Xe that are roughly equal but opposite in sign, then the allowed region might be expanded very slightly above our nominal 20-GeV bound. For larger masses where both a neutron-only and a proton-only SD interaction are ruled out at a significant level, any combination of proton and neutron SD interactions will also be inconsistent.

5. Conclusion

The annual modulation observed in the DAMA low-energy bins has been attributed to a WIMP with SI interactions with nuclei, a possibility in contradiction with null searches by CDMS. However, this is *a priori* not the only interpretation — the modulation could also be due most generally to a WIMP with SD interactions.

We have shown here that the region of parameter space implied by the DAMA signal for a WIMP that undergoes SD scattering from protons is excluded in a model-independent way by null searches for a WIMP-induced energetic-neutrino flux from the Sun.

The alternative hypothesis — that the modulation is due to WIMP scattering from neutrons — is excluded for $M_\chi \gtrsim 20\,\mathrm{GeV}$ by data taken with a Xe detector. Although experimentally viable, the $M_\chi \lesssim 20\,\mathrm{GeV}$ solution requires new physics beyond the minimal supersymmetric standard model [16]. More importantly, it requires that the WIMP-proton and WIMP-neutron interactions differ by more than four orders of magnitude. Such a large difference would be quite unusual.

The SD WIMP parameters compatible with the DAMA modulation derived here may be slightly changed by including particle and nuclear uncertainties or uncertainties in the local WIMP velocity distribution [17], as well as by performing a more accurate analysis on the raw data. However all these effects cannot account for the order-of-magnitude (or more) discrepancies pointed out here.

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