PHYSICAL REVIEW D **67**, 103507 (2003)

Comparing interaction rate detectors for weakly interacting massive particles with annual modulation detectors

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(Received 31 July 2002; revised manuscript received 4 March 2003; published 19 May 2003)

We compare the sensitivity of WIMP detection via direct separation of possible signal versus background to WIMP detection via detection of an annual modulation, in which signal and background cannot be separated on an event-by-event basis. In order to determine how the constraints from the two different types of experiments might be combined an adequate incorporation of uncertainties due to galactic halo models must be made. This issue is particularly timely in light of recent direct detection limits from Edelweiss and CDMS, which we now demonstrate cannot be made consistent with the most recent claimed DAMA annual modulation observation by including halo uncertainties for spin independent interactions. On the other hand, we demonstrate that a combination of these two techniques, in the event of any positive direct detection signal, could ultimately allow significant constraints on anisotropic halo models even without directional sensitivity in these detectors.

DOI: 10.1103/PhysRevD.67.103507 PACS number(s): 95.35.+d

The recent results from the weakly interacting massive particle (WIMP) direct detection experiments CDMS [1] and the annual modulation-sensitive DAMA detector [2] appear inconsistent. Indeed, they have been claimed to be incompatible at the $>99.98\%$ level [1]. This compatibility estimate is based on the assumption that the dark matter halo in our Galaxy is well described by an isothermal sphere with a velocity dispersion of 220 km/s (the standard model) for the local velocity distribution of WIMPs and that WIMPs undergo spin independent interactions with nuclei. We will also focus on spin independent interactions for our calculations, however, because these two different types of experiments are searching for different WIMP signals the WIMP halo distribution can play a key role in determining the constraints derived from the experimental results. As a result, the actual level of inconsistency between CDMS and DAMA is likely to be strongly model-dependent. More recently, however, a new result from the Edelweiss [3] detector puts a stronger bound on WIMP cross sections for much of the mass range that is apparently favored by the DAMA result. This makes the question of the possible significance of halo model uncertainties more timely—namely, in light of this new result, is there any room left for astrophysical uncertainties to allow a reconciliation of the DAMA result with the CDMS-Edelweiss result? Motivated by this fact, we explore here a wide range of analytic halo models to examine their effects on the expected WIMP signatures in these two different types of detectors, and present several new ways of comparing the data. We derive two main results: (1) Halo model uncertainties do not allow a reconciliation of the DAMA result with the CDMS-Edelweiss results, and (2) a combination of these two techniques could ultimately provide sensitivity to anisotropies in a galactic WIMP halo even if direct detection experiments do not have directional sensitivity. Using pulse shape discrimination to identify nuclear recoils, NaI or CsI crystals may provide a probe of the WIMP halo distribution in this way [4].

CDMS is a cryogenic detector that is capable of measuring the full energy of the recoiling nucleus. Since both the electronic and photonic channels are measured they have excellent background rejection and can thus look for individual nuclear recoil events. The signal they are searching for is an excess of nuclear recoil events above their expected backgrounds. With 10.6 kg d of data they found no excess events above the expected neutron background [1]. Edelweiss uses the same detector technology as CDMS but is in a deep underground site so that sophisticated background subtraction is unnecessary. With 7.4 kg d of data no WIMP events were found. The two results are consistent and complementary. CDMS is most sensitive for low mass WIMPs ($m_\chi \lesssim 35$ GeV) and Edelweiss is most sensitive for higher mass WIMPS ($m_\chi \gtrsim 35$ GeV). When combined these two experiments rule out essentially all of the DAMA region for the standard halo model.

DAMA consists of high purity NaI crystals run in a deep site. They have no particle identification and thus have no background subtraction capabilities. However, the detector mass is large so many events (background and possible signal) can be recorded. A modulation of the rate is expected due to the Earth's motion around the Sun (and thus through the WIMP halo) and any such modulation in the event rate provides a potential WIMP signature. With 57 986 kg d of data they indeed report a modulation signal that is claimed to be consistent with WIMP scattering. From this a mass and cross section for WIMPs can be determined.

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Heuristically one can see that the halo model will affect the modulation signal and the overall rate in different ways. Consider the standard halo model. If we decrease the velocity dispersion (narrow the Gaussian) we decrease the number of WIMPs in the tails of the distribution; in particular we decrease the number of WIMPs with high velocity that can lead to high energy nuclear recoils. Thus the overall rate one expects to observe is decreased. However, at the same time the size of the modulation signal is increased because with fewer high velocity WIMPs the Earth's motion around the Sun becomes a larger perturbation on the net WIMP velocity as measured in the laboratory frame.

Naturally these statements depend on the a number of factors. In particular the size of the effect depends on the masses of the WIMP and target nucleus and on the velocity of the Earth (magnitude and direction) with respect to the WIMP halo. Here we will analyze a set of analytic halo models. The procedure for calculating WIMP scattering rates is well known [5–7]. We briefly discuss some aspects here.

The differential scattering rate for a WIMP of mass m_χ from a nucleus with atomic number A_N is given by

$$\frac{dR}{dQ}=\frac{(m_n+m_\chi)^2A_N^2\sigma_p\rho_0}{2m_n^2m_\chi^3}F^2(Q)\int\frac{f(\mathbf{v})}{|\mathbf{v}|}d^3v. \qquad (1)$$

Here Q is the recoil energy of the nucleus, m_n is the mass of a nucleon (taken to be a proton), $F^2(Q)$ is the nuclear form factor which we take to be the standard Helm form [8], ρ_0 is the local halo density of WIMPs, and $f(\mathbf{v})$ is the local WIMP halo velocity distribution.

For CDMS-Edelweiss the target nucleus is Ge ($A_{\mathrm{Ge}}=73$), the full energy is measured so quenching is not an issue, and they are sensitive to 10–100 keV recoils (CDMS) and $\geqslant 20$ keV (Edelweiss). For DAMA the detector consists of two nuclei, sodium ($A_{\mathrm{Na}}=23$) and iodine ($A_{\mathrm{I}}=127$). Only the ionization energy is measured so only a fraction of the energy is detected. Note that DAMA claims to observe a modulation signal for measured recoil energies (i.e., with quenching) in the range 2–6 keV. We use $q_{\mathrm{Na}}=0.30$ and $q_{\mathrm{I}}=0.09$ to convert between the actual and detected energies. We incorporate their finite energy resolution in our calculations [9].

We probe a range of halo models ranging from spherically symmetric to triaxial to discontinuous. These models have been studied in the context of the angular signal expected in future detectors possessing angular resolution and more details and references can be found there [10]. Briefly, we consider the isothermal model, an axisymmetric Evans model, a triaxial halo model, and a model of caustics that leads to WIMP flows in velocity space. For the isothermal model we consider dispersions of $v_0=170$ km/s, 220 km/s, and 270 km/s to account for observational uncertainties. These models have been discussed in the context of WIMP detection. For demonstration purposes we explore here the effect of varying halo models on the modulation signal in NaI detectors using parameters from DAMA and the overall rate using parameters from CDMS.

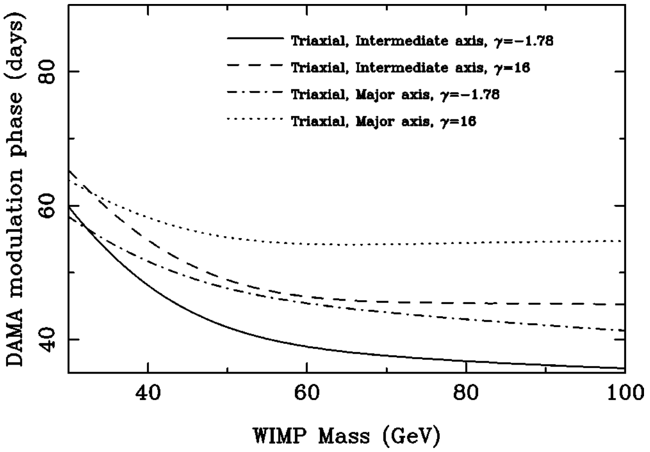

FIG. 1. Modulation phase for nonsymmetric halo distributions. For the standard model the phase is 152.5 days.

For the modulation signal there are two important parameters, the amplitude of the modulation (related to the WIMP cross section) and the phase of the modulation. For symmetric models (such as the isothermal and Evans halos) since all directions through the halo are approximately equivalent, the modulation should be in phase with the motion of the Earth around the Sun. Thus the phase $t_p=152.5$ days. For nonsymmetric halos the direction of motion through the halo is important and can lead to maximal scattering at different times in the Earth's orbit. The resulting phase for such models is given in Fig. 1 as a function of WIMP mass. Notice that in all cases the phase is quite different from the standard model $t_p=152.5$ days.

In comparing the CDMS-Edelweiss and DAMA results using the standard isothermal halo, we confirm the CDMS analysis that the DAMA claimed modulation corresponds to a rate that should have been observed in CDMS. The key question, however is, whether the same result applies for all possible halo models, so we have calculated the expected rate and modulation amplitude for CDMS-Edelweiss and DAMA as a function of WIMP mass for a wide range of models. To quantify our results, we present a novel way of comparing models. We consider the ratio of the rate from a particular model to the rate from the standard model (for CDMS-Edelweiss), and likewise the ratio of the modulation amplitudes for the models (for DAMA). If the ratio in the latter case is larger than 1, then the WIMP cross section need not be as large to produce the same measured modulation. This in turn will lower the best fit region from DAMA. Alternatively, if the former ratio is less than unity, this will raise the CDMS-Edelweiss upper limit on the WIMP cross section.

Some variations will change both ratios in the same direction. For example, decreasing the local halo WIMP density will lower the overall CDMS-Edelweiss rate, however it will also lower the DAMA modulation amplitude in the same way leading to no overall net effect in the comparison of the two experiments. We thus present a fiducial quantity which cancels out such effects: we take the ratio of the DAMA

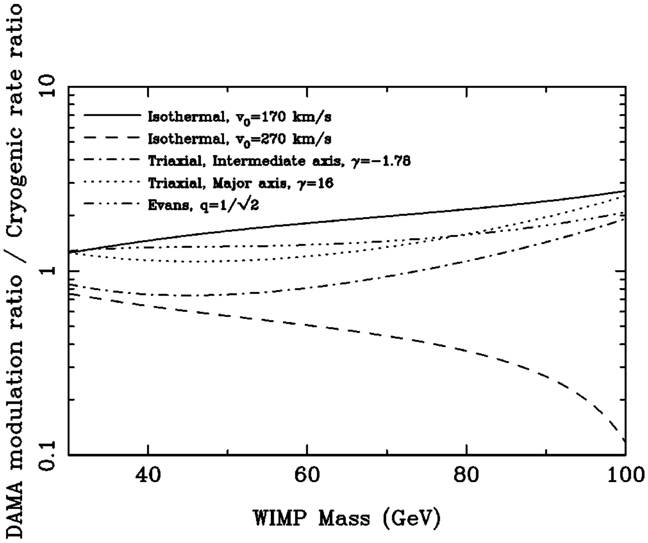

FIG. 2. The ratio of the DAMA modulation ratio to the CDMS-Edelweiss rate ratio as a function of WIMP mass. For the standard model this ratio is one. Models for which this ratio is greater than one lead to better agreement between the experiments whereas models for which this ratio is less than one lead to more disagreement.

modulation ratio to the CDMS-Edelweiss rate ratio (Fig. 2) as a function of mass. For each mass the standard model is one. Models for which this ratio is greater than one lead to less overlap between the CDMS-Edelweiss limit and the DAMA claimed observation, and hence reduce disagreement between these experiments, whereas a ratio less than one leads to more overlap and hence greater disagreement.

From Fig. 2 one can see, as expected, that a narrower velocity dispersion in an isothermal distribution ($v_0 = 170$ km/s) leads to a ratio greater than one and a broader isothermal distribution ($v_0 = 270$ km/s) leads to a ratio less than one. In fact the narrower isothermal distribution has the largest deviation from the standard model in the direction necessary to reconcile the two experiments of any of the models we examined. Most halo models fall between the two extremes set by the isothermal models. A flattened axisymmetric model (Evans model) also provides some improvement over the standard model. Triaxial models can lead to either larger or smaller ratios for a detector with the sensitivity of DAMA depending on the orientation of the axes.

Quantitatively, the maximum improvement we find for any model in the agreement between CDMS-Edelweiss and DAMA is about 2.7 (at $m_\chi = 100$ GeV). In general potential agreement between the experiments improves at larger WIMP mass. For the case of CDMS alone, this would open up a potentially significant range of parameter space in which the DAMA result might be compatible since CDMS is most sensitive at lower masses. However, when the Edelweiss result is included, this factor would effectively make the new Edelweiss limit comparable to, but still stronger than, the older CDMS standard halo model result at the higher masses, which is claimed to be incompatible with DAMA as noted above. Based on this claim then, CDMS-Edelweiss and DAMA are now seen to be incompatible, *independent of halo model uncertainties*.

Our analysis can be extended to other experiments. For example, ZEPLIN-I, a liquid xenon detector, has also recently published a limit that cuts deeply into the DAMA region [12]. Though not as sensitive as Edelweiss, it provides an independent probe of parameter space. For the isothermal model with $v_0 = 170$ km/s we find the limits scales in a way similar to Edelweiss and does not provide a stronger limit.

We note that while halo uncertainties are not sufficient to explain the CDMS-Edelweiss-ZEPLIN-I discrepancy with DAMA for spin independent WIMP-nucleon interactions, other possible resolutions remain. For example, natural germanium only contains about 8% nuclei with a nonzero spin, whereas natural sodium and iodine consist entirely of nuclei with nonzero spin. Thus, if the interaction is dominantly spin dependent, rather than spin independent, the sensitivity of CDMS-Edelweiss would be reduced. (Note that spin dependent cross sections are in general expected to be smaller than spin independent cross sections.) However, this would not necessarily resolve the apparent discrepancy between ZEPLIN-I and DAMA. Since natural xenon contains about 50% nuclei with a nonzero spin it would still be quite sensitive to spin-dependent interactions. In the spin-dependent case, detailed nuclear physics models of the nuclei in question (which differ significantly) are required in order for a realistic comparison to be made, and important nuclear physics uncertainties will affect the conclusions one might derive in this case.

There is one other important astrophysical consideration in addition to the amplitude of any annual modulation. As seen from Fig. 1, the phase of the modulation in triaxial models will not in general agree with the predicted phase from the standard isothermal model, which is in agreement with the DAMA data. This is an important effect. Not only does it rule out these models as possibilities for allowing a reconciliation of DAMA and CDMS, if DAMA, or any eventual annual modulation observation has a phase in agreement with the standard model, then these models will be severely constrained. Alternatively, and perhaps more interestingly, for low mass WIMPs observing this phase of any annual modulation will tell us something about the orientation of the axes in a triaxial model *without the need for a detector with angular sensitivity*.

As suggested by the above, the analysis performed here has application beyond a mere comparison of DAMA and CDMS or Edelweiss, where our analysis suggests the DAMA annual modulation disagreement with the latter two experiments cannot be explained by changing the halo model. The general method demonstrates both the effect of galactic halo uncertainties on any comparison of overall interaction rates with annual modulation in untangling WIMP parameters from direct detection experiments, and also the possible utility of performing such a comparison if eventually WIMPs are observed in both sets of experiments. In particular important information can be gleaned that might complement that which can be obtained in detectors with angular sensitivity [11].

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