Implications of the DAMA/NaI and CDMS experiments for mirror matter-type dark matter

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We re-analyse the implications of the DAMA/NaI experiment for mirror matter-type dark matter, taking into account information from the energy dependence of the DAMA annual modulation signal. This is combined with the null results from the CDMS experiment, leading to fairly well defined allowed regions of parameter space. The allowed regions of parameter space will be probed in the near future by the DAMA/LIBRA, CDMS, and other experiments, which should either exclude or confirm this explanation of the DAMA/NaI annual modulation signal. In particular, we predict that the CDMS experiments should find a positive signal around the threshold recoil energy region, $E_R < 15$ keV in the near future.

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1 Introduction

The exact parity symmetric model\cite{1} is the minimal extension of the standard model which allows for an exact unbroken parity symmetry $[x \rightarrow -x, t \rightarrow t]$. According to this theory, each type of ordinary particle (electron, quark, photon etc) has a corresponding mirror partner (mirror electron, mirror quark, mirror photon etc), of the same mass. The two sets of particles form parallel sectors each with gauge symmetry $G$ (where $G = SU(3) \otimes SU(2) \otimes U(1)$ in the simplest case) so that the full gauge group is $G \otimes G$. The unbroken mirror symmetry maps $x \rightarrow -x$ as well as ordinary particles into mirror particles. Exact unbroken time reversal symmetry also exists, with standard CPT identified as the product of exact $T$ and exact $P$\cite{1}.

It has been argued that the stable mirror particles, mirror nucleons and mirror electrons are an interesting candidate for the inferred dark matter of the Universe (for a review, see Ref.\cite{2}). Of course, to be a successful dark matter candidate, mirror matter needs to behave, macroscopically, differently to ordinary matter. In particular, four key distinctions need to be explained:

- The cosmological abundance of mirror matter should be different to ordinary matter, $\Omega_{\text{dark}} \neq \Omega_{\text{matter}}$.
- Mirror particles should give negligible contribution to the energy density at the epoch of big bang nucleosynthesis.
- Structure formation in the mirror sector must begin before ordinary matter radiation decoupling.
- In spiral galaxies, the time scale for the collapse of ordinary matter onto the disk must be much shorter than that of mirror matter.

Clearly, mirror matter behaves differently to ordinary matter, at least macroscopically. It is hypothesised that this macroscopic asymmetry originates from effectively different initial conditions in the two sectors. The exact microscopic (Lagrangian) symmetry between ordinary and mirror matter need never be broken. In particular, if ordinary and mirror particles have different temperatures in the early Universe, $T' \ll T$, then the mirror particles give negligible contribution to the energy density at the time of nucleosynthesis leading to standard big bang nucleosynthesis. Another consequence of $T' \ll T$ is that mirror photon decoupling occurs earlier than ordinary photon decoupling – implying that mirror structure formation can begin before ordinary photon decoupling. In this way, mirror matter-type dark matter can successfully explain the large scale structure formation (for detailed studies, see ref.\cite{3, 4, 5}). Also, $\Omega_{\text{dark}} \neq \Omega_{\text{matter}}$ could also be due to different effective initial conditions in the early Universe (see e.g. ref.\cite{6},\cite{7} for some specific scenarios).

If mirror matter is the inferred non-baryonic dark matter in the Universe, then the halo of our galaxy should be gas of ionized mirror atoms and mirror electrons together with a non-gaseous component of $f \sim 0.2$ (which can be inferred from gravitational microlensing studies\cite{8}). Although dissipative, roughly spherical galactic
mirror matter halo’s can exist without collapsing provided that a heating mechanism exists - with ordinary and/or supernova explosions being plausible candidates[9]. Obviously, the heating of the ordinary and mirror matter in spiral galaxies needs to be asymmetric, but again, due to different initial conditions in the early Universe, asymmetric heating is plausible. For example, the early Universe temperature asymmetry, $T' \ll T$ (expected from successful big bang nucleosynthesis and Large scale structure formation, as discussed above) implies that the primordial mirror helium/mirror hydrogen ratio will be much larger than the corresponding ordinary helium/ordinary hydrogen ratio[3]. Consequently the formation and evolution of stars in the ordinary and mirror sectors are completely different. The details of the evolution on (sub) galactic scales, is of course, very complex, and is yet to be fully understood.

Ordinary and mirror particles interact with each other by gravity and via photon-mirror photon kinetic mixing:

$$L = \frac{e}{2} F^{\mu\nu} F_{\mu\nu}$$

where $F^{\mu\nu}$ ($F_{\mu\nu}'$) is the field strength tensor for electromagnetism (mirror electromagnetism). One effect of photon-mirror photon kinetic mixing is to cause mirror charged particles (such as the mirror proton and mirror electron) to couple to ordinary photons with effective electric charge $\epsilon e$. [1, 12, 13] The various experimental implications of photon-mirror photon kinetic mixing have been reviewed in Ref.[14]. Of most relevance for this paper, is that this interaction enables mirror particles to elastically scatter off ordinary particles – essentially Rutherford scattering.

A detector on Earth can therefore be used to detect halo mirror nuclei via elastic scattering. Several previous papers[15, 16, 17] have explored this possibility, especially in view of the impressive dark matter signal from the DAMA/NaI experiment[18]. The purpose of this paper is to re-analyse the mirror matter interpretation of the DAMA/NaI experiment in combination with the null results of the CDMS experiment[19] in order to pin down more precisely the currently favoured region of parameter space within this scenario.

The outline of this paper is as follows: In section 2 we review and extend the Mirror matter interpretation of the positive DAMA/NaI annual modulation signal. In section 3 we utilize the measured recoil energy dependence of the DAMA/NaI annual modulation signal to constrain the mirror matter interpretation. In section 4 we then examine the implications of the null results obtained in the CDMS/Ge experiment. Importantly, we find that there is a fairly significant allowed region of parameter space consistent with the positive DAMA/NaI annual modulation signal and the null results of the CDMS experiment. Finally in section 5 we conclude.

Technically, photon-mirror photon kinetic mixing arises from kinetic mixing of the $U(1)$ and $U(1)'$ gauge fields, since only for the abelian $U(1)$ gauge symmetry is such mixing gauge invariant[10]. The only other gauge invariant and renormalizable interactions mixing ordinary and mirror particles are the quartic Higgs - mirror Higgs interaction: $\lambda \phi^\dagger \phi \phi'^\dagger \phi'$ and neutrino - mirror neutrino mass mixing[1, 11].
2 Mirror dark matter implications for direct detection experiments such as DAMA/NaI

Let us first briefly review the required technology (see references [15, 16, 17] for more details). For definiteness, consider a halo mirror nuclei, \( A' \), of atomic number \( Z' \) scattering off an ordinary nucleus, \( A \) (in an ordinary matter detector) of atomic number \( Z \). The cross section is then just of the standard Rutherford form corresponding to a particle of electric charge \( Z e \) scattering with a particle of electric charge \( \epsilon Z'e \). This cross section can be expressed in terms of the recoil energy of the ordinary atom, \( E_R \), and the velocity in the Earth’s rest frame, \( v \):

\[
\frac{d\sigma}{dE_R} = \frac{\lambda}{E_R^2 v^2}
\]

where

\[
\lambda \equiv \frac{2\pi\epsilon^2\alpha^2 Z^2 Z'^2}{M_A} F_A^2(qr_A) F_{A'}^2(qr_{A'})
\]

and \( F_X(qr_X) \) (\( X = A, A' \)) are the form factors which take into account the finite size of the nuclei and mirror nuclei. \( q = (2M_A E_R)^{1/2} \) is the momentum transfer and \( r_X \) is the effective nuclear radius\(^3\). A simple analytic expression for the form factor, which we adopt in our numerical work, is the one given by Helm [20, 21]:

\[
F_X(qr_X) = 3 \frac{j_1(qr_X)}{qr_X} e^{-qs^2/2}
\]

with \( r_X = 1.14X^{1/3} \) fm, \( s = 0.9 \) fm. In this equation, \( j_1 \) is the spherical Bessel function of index 1.

In an experiment such as DAMA/NaI\(^{18} \), the measured quantity is the recoil energy, \( E_R \), of a target atom. The interaction rate is

\[
\frac{dR}{dE_R} = \sum_{A'} N_T n_{A'} \int \frac{d\sigma}{dE_R} f_{A'}(v, v_E) \frac{|v|}{k} d^3v
\]

\[
= \sum_{A'} N_T n_{A'} \int_{|v| > v_{\text{min}}(E_R)} \frac{f_{A'}(v, v_E) d^3v}{k |v|}
\]

where \( N_T \) is the number of target atoms per kg of detector\(^4\). Also, \( n_{A'} \) is the halo number density (at the Earth’s location) of the mirror element, \( A' \) and \( f_{A'}(v, v_E)/k \) is its velocity distribution \( (k \) is the normalization factor) with \( v \) being the velocity relative to the Earth, and \( v_E \) is the Earth velocity relative to the dark matter distribution. The lower velocity limit, \( v_{\text{min}}(E_R) \), is given by the kinematic relation:

\[
v_{\text{min}} = \sqrt{\frac{(M_A + M_{A'})^2 E_R}{2M_A M_{A'}^2}}.
\]

\(^3\)We use natural units, \( \hbar = c = 1 \) throughout.

\(^4\)For detectors with more than one target element we must work out the event rate for each element separately and add them up to get the total event rate.
Considering a particular mirror chemical element, \( A' \) (e.g. \( A' = H', He', O' \) etc), the velocity distribution for these halo mirror particles is then:

\[
f_{A'}(v, v_E) = \exp\left[ -\frac{1}{2} M_{A'} (v + v_E)^2 / T \right] = \exp\left[ -(v + v_E)^2 / v_0^2 \right]
\]

where \( v_0^2 \equiv 2T/M_{A'} \). The assumption of approximate hydrostatic equilibrium for the halo particles implies a relation between \( T \) and the local rotational velocity, \( v_{rot} \):

\[
T = \frac{\mu M_p v_{rot}^2}{2}
\]

where \( \mu M_p \) is the mean mass of the particles comprising the mirror (gas) component of the halo (\( M_p \) is the proton mass). Note that the Maxwellian distribution should be an excellent approximation in the case of mirror dark matter, since the self interactions of the particles ensure that halo is thermalized.

The velocity integral in Eq.(5),

\[
I(E_R) \equiv \int_{|v|>v_{min}(E_R)} f_{A'}(v, v_E) \frac{k|v|}{d^3v}
\]

is standard (similar integrals occur in the usual WIMP interpretation\(^5\) ) and can easily be evaluated in terms of error functions assuming a Maxwellian dark matter distribution\([21]\),

\[
f_{A'}(v, v_E)/k = (\pi v_0^2)^{-3/2} \exp[-(v + v_E)^2 / v_0^2],
\]

\[
I(E_R) = \frac{1}{2v_0y} [erf(x + y) - erf(x - y)]
\]

where

\[
x \equiv \frac{v_{min}(E_R)}{v_0}, \quad y \equiv \frac{v_E}{v_0}.
\]

The Earth’s velocity relative to the galaxy, \( v_E \), has an estimated mean value of \( \langle v_E \rangle \approx v_{rot} + 12 \text{ km/s} \), with \( v_{rot} \), the local rotational velocity, in the 90% C.L. range\([22]\),

\[
170 \text{ km/s} \lesssim v_{rot} \lesssim 270 \text{ km/s}.
\]

While some estimates put more narrow limits on the local rotational velocity, it is useful to allow for a broad range for \( v_{rot} \) since it can also approximate the effect of bulk halo rotation.

As can be seen from Eq.(7,8), in the case of mirror matter-type dark matter, the \( v_0 \) value for a particular halo component element, \( A' \), depends on the chemical composition of the halo. In general,

\[
\frac{v_0^2(A')}{v_{rot}^2} = \frac{\mu M_p}{M_{A'}}
\]

\(^5\)However in the WIMP case the upper velocity limit is finite, corresponding to the galactic escape velocity. While for mirror dark matter, the upper limit is infinite due to the self interactions of the mirror particles.
The most abundant mirror elements are expected to be $H', He'$, generated in the early Universe from mirror big bang nucleosynthesis (heavier mirror elements should be generated in mirror stars). It is useful, therefore, to consider two limiting cases: first that the halo is dominated by $He'$ and the second is that the halo is dominated by $H'$. The mean mass of the particles in the halo are then (taking into account that the light halo mirror atoms should be fully ionized):

$$\mu M_p \simeq \frac{M_{He'}}{3} \simeq 1.3 \text{ GeV for } He' \text{ dominated halo},$$

$$\mu M_p \simeq \frac{M_{H'}}{2} \simeq 0.5 \text{ GeV for } H' \text{ dominated halo}. \quad (14)$$

The $v_0$ values can then easily be obtained from Eq.(13):

$$v_0(A') = v_0(He')\sqrt{\frac{M_{He'}}{M_{A'}}} \approx v_{\text{rot}} \sqrt{3} \text{ km/s for } He' \text{ dominated halo}$$

$$v_0(A') = v_0(H')\sqrt{\frac{M_{H'}}{M_{A'}}} \approx v_{\text{rot}} \sqrt{2} \text{ km/s for } H' \text{ dominated halo}. \quad (15)$$

Mirror BBN[3] suggests that $He'$ dominates over $H'$, and this is what we assume in our numerical work in this paper. However, it turns out that the thresholds of the DAMA/NaI and CDMS experiments are sufficiently high that these experiments are only sensitive to mirror elements heavier than about carbon, which means that $v_0(A') \ll v_{\text{rot}}$ for these elements – independently of whether $He'$ or $H'$ dominates the halo. For this reason, our main results (such as the allowed regions in figure 4) do not depend very significantly on whether we assume that $He'$ or $H'$ dominates the mass of the Halo.

The DAMA/NaI experiment[18] turns out to be very sensitive to mirror matter-type dark matter because of the light target element, $Na$, and the relatively low energy threshold of 2 keVee\(^6\). This experiment uses the annual modulation signature[23], which arises because of the Earth’s motion around the sun. The point is that the interaction rate, Eq.(5), depends on $v_E$, which varies due to the Earth’s motion around the sun:

$$v_E(t) = v_\odot + v_\oplus \cos \gamma \cos \omega (t - t_0)$$

$$= v_\odot + \Delta v_E \cos \omega (t - t_0) \quad (16)$$

where $v_\odot = v_{\text{rot}} + 12 \text{ km/s} \sim 230 \text{ km/s}$ is the sun’s velocity with respect to the galaxy and $v_\oplus \simeq 30 \text{ km/s}$ is the Earth’s orbital velocity around the Sun ($t_0 = 152.5 \text{ days}$ and $\omega = 2\pi/T$, with $T = 1 \text{ year}$). The inclination of the Earth’s orbital plane relative to the galactic plane is $\gamma \simeq 60^\circ$, which implies that $\Delta v_E \simeq 15 \text{ km/s}$. The differential interaction rate, Eq.(5), can be expanded in a Taylor series around $v_E = v_\odot$, leading to an annual modulation term:

$$R_i = R_i^0 + R_i^1 \cos \omega (t - t_0) \quad (17)$$

\(^6\)The unit, keVee is the so-called electron equivalent energy, which is the energy of the event if due to an electron recoil. The actual nuclear recoil energy (in keV) is given by: $\text{keVee} / q$, where $q$ is the quenching factor ($q_I \simeq 0.09$ and $q_{Na} \simeq 0.30$).
where

\[
R^0_i = \frac{1}{\Delta E} \int_{E_i}^{E_i + \Delta E} \left( \frac{dR}{dE_R} \right)_{v_E = v_\odot} dE_R,
\]

\[
R^1_i = \frac{1}{\Delta E} \int_{E_i}^{E_i + \Delta E} \frac{\partial}{\partial v_E} \left( \frac{dR}{dE_R} \right)_{v_E = v_\odot} \Delta v_E dE_R \quad (18)
\]

According to the DAMA analysis\[18\], they indeed find an annual modulation at more than 6\(\sigma\) C.L. Their data fit gives \(T = (1.00 \pm 0.01)\) years and \(t_0 = 140 \pm 22\) days, consistent with the expected values. [The expected value for \(t_0\) is 152.5 days (2 June), where the Earth’s velocity reaches a maximum with respect to the galaxy]. Their signal occurs in the 2-6 keVee energy range, with amplitude

\[
R^1 = (0.019 \pm 0.003) \text{ cpd/kg/keVee} \quad \text{[cpd = counts per day].} \quad (19)
\]

The DAMA experiment itself is not sensitive to the dominant, \(He'\) or \(H'\) component. These nuclei are too light to give a signal above the DAMA/NaI energy threshold. DAMA is sensitive to mirror nuclei heavier than about carbon. In this paper, we propose to approximate the spectrum of such heavy mirror metals by three components, \(O', Si', Fe'\), which span the expected mass range. In principle it might be possible to predict the relative abundances of the mirror metal components if enough is known about the initial conditions and stellar evolution in the mirror sector (for some preliminary work in this direction, see ref.[24]). However, for the purposes of this paper, we leave the relative abundances of these three components as free parameters to be fixed by the direct detection experiments.

Interpreting the DAMA annual modulation signal [Eq.(19)] in terms of these three elements and assuming a \(He'\) dominated halo, we find numerically that[25]:

\[
|\epsilon| \sqrt{\xi_{O'} + \frac{\xi_{Si'}}{0.016} + \frac{\xi_{Fe'}}{0.015}} \approx 5.3^{2.4}_{-1.4} \times 10^{-9} \quad \text{for} \quad v_{\text{rot}} = 220 \text{ km/s}, \quad (20)
\]

where the errors denote a 3 sigma allowed range [i.e. \(R^1 = 0.019 \pm 0.009 \text{ cpd/kg/keVee}\)] and \(\xi_{A'} \equiv n_{A'} M_{A'}/(0.3 \text{ GeV/cm}^3)\) is the \(A'\) proportion (by mass) of the halo dark matter. Allowing for a range of \(v_{\text{rot}}\), we find

\[
|\epsilon| \sqrt{\xi_{O'} + \frac{\xi_{Si'}}{0.004} + \frac{\xi_{Fe'}}{7.2 \times 10^{-4}}} \approx 1.4^{0.3}_{-0.2} \times 10^{-8} \quad \text{for} \quad v_{\text{rot}} = 170 \text{ km/s}
\]

\[
|\epsilon| \sqrt{\xi_{O'} + \frac{\xi_{Si'}}{0.034} + \frac{\xi_{Fe'}}{0.083}} \approx 4.3^{0.9}_{-1.2} \times 10^{-9} \quad \text{for} \quad v_{\text{rot}} = 250 \text{ km/s} \quad (21)
\]

Evidently, the magnitude of \(|\epsilon|\sqrt{\sum \xi_{A'}}\) depends somewhat on \(v_{\text{rot}}\).

Note that mirror matter with \(\epsilon \sim 10^{-9}\) has many interesting applications (see e.g. ref. [26, 27]). It is also consistent with Laboratory[28] and big bang nucleosynthesis constraints[29].
3 Recoil energy dependence of the annual modulation signal

The relative abundance of the $O'$, $Si'$ and $Fe'$ components can in principle be determined from the annual modulation energy spectrum [ defined as $R^1 \equiv \frac{\partial}{\partial v_E} \left( \frac{\partial R}{\partial E} \right) \Delta v_E ]$. In Figure 1a,b,c, we give the predicted DAMA/NaI annual modulation energy spectrum for $He'$ dominated halo assuming a mirror metal component consisting of a) pure $O'$ ($\xi_{Fe'} = \xi_{Si'} = 0$), b) pure $Si'$ ($\xi_{O'} = \xi_{Fe'} = 0$) and c) pure $Fe'$ ($\xi_{O'} = \xi_{Si'} = 0$), for three representative values for $v_{rot}$. In each case, $|\epsilon| \sqrt{\xi}$ is fixed so that $R^1 = 0.019$ cpd/kg/keVee in the $(2 - 6)$ keVee region.

Figure 1a: DAMA/NaI annual modulation energy spectrum (as defined in text) with $\xi_{Si'} = \xi_{Fe'} = 0$ and $|\epsilon| \sqrt{\xi_{O'}}$ fixed so that $R^1 = 0.019$ cpd/kg/keVee in the 2-6 keVee region.
Figure 1b: DAMA/NaI annual modulation energy spectrum, with $\xi_{O'} = \xi_{Fe'} = 0$ and $|\epsilon|\sqrt{\xi_{Si'}}$ fixed so that $R^1 = 0.019$ cpd/kg/keVee in the 2-6 keVee region.

Figure 1c: DAMA/NaI annual modulation energy spectrum, with $\xi_{O'} = \xi_{Si'} = 0$ and $|\epsilon|\sqrt{\xi_{Fe'}}$ fixed so that $R^1 = 0.019$ cpd/kg/keVee in the 2-6 keVee region.
As the figures illustrate, the spectrum for the pure $O'$ case is very steep, with negligible annual modulation in the (4-6) keVee region. $Si'$ and especially the $Fe'$ case, on the other hand, are much flatter. Of course, this behaviour is very easy to understand: the heavier elements, impacting with the Earth with typical velocity, $\sim v_{\text{rot}}$, can transfer more momentum to the target nuclei, and thus can give a significant signal at larger recoil energies. Importantly, there is a negligible region of parameter space which gives a significant annual modulation above 6 keVee – consistent with the DAMA/NaI experiment which only observed an annual modulation below 6 keVee.[18]

Information about the annual modulation energy spectrum can be obtained from the published measurements[18]:

\[
\begin{align*}
R^1[(2-4)\text{keVee}] &= 0.0233 \pm 0.0047 \text{ cpd/kg/keVee} \\
R^1[(2-5)\text{keVee}] &= 0.0210 \pm 0.0038 \text{ cpd/kg/keVee} \\
R^1[(2-6)\text{keVee}] &= 0.0192 \pm 0.0031 \text{ cpd/kg/keVee}
\end{align*}
\] (22)

In particular, we can infer from the above that the annual modulation is likely to be non-negligible in the (4-6) keVee region:

\[
R^1[(4-6)\text{keVee}] = 0.015 \pm 0.005 \text{ cpd/kg/keVee}
\] (23)

Clearly, this suggests that $Si'$ and/or $Fe'$ are non-negligible component(s). This can be quantified, by considering the (approximate) 2$\sigma$ range: $0.005 < R^1[(4-6)\text{keVee}] < 0.025$, with $A[(2-6)\text{keVee}] = 0.019$. This is equivalent to:

\[
0.26 < \frac{R^1[(4-6)\text{keVee}]}{R^1[(2-6)\text{keVee}]} < 1.32
\] (24)

In figure 2, we plot the allowed region of parameter space consistent with this constraint. We vary $\xi_{Si'}$, for 3 fixed values for $\xi_{Fe'}$. 


Figure 2a: Region of parameter space ($\sim 2\sigma$ allowed region) consistent with the DAMA/NaI annual modulation energy spectrum constraint, $0.26 < R^1[(4-6)\text{keVee}] / R^1[(2-6)\text{keVee}] < 1.32$. This figure assumes $\xi_{Fe'} = 0$.

Figure 2b: Same as figure 2a, except, $\xi_{Fe'}/(\xi_{Si'} + \xi_{O'} + \xi_{Fe'}) = 0.02$. 
4 The CDMS/Ge experiment

We now turn to the CDMS/Ge experiment[19]. This experiment has a threshold of 10 keV with a germanium target. Unlike the DAMA/NaI experiment, the CDMS/Ge experiment is not sensitive to the annual modulation effect, but aims to measure the absolute interaction rate (which we approximate by fixing $v_E = v_\odot$):

$$\frac{dR}{dE_R} |_{v_E = v_\odot} = \sum_{A'} N_{Tn_{A'}} \int \frac{d\sigma}{dE_R} \frac{f_{A'}(v, v_E = v_\odot)}{k} |v| d^3v$$

$$= \sum_{A'} N_{Tn_{A'}} \frac{\lambda}{E_R^2} \int_{|v| > v_{\text{min}}(E_R)} f_{A'}(v, v_E = v_\odot) \frac{k|v|}{d^3v}$$

The CDMS event rate is the product of the interaction rate and over-all detection efficiency. With 52.6 kg-days of raw exposure, they obtained no events passing their detection criteria. Using their published detection efficiency (figure 3 of ref.[19]), We can predict the expected number of events, fixing $|\epsilon| \sqrt{\xi}$ using the positive DAMA/NaI annual modulation signal. Of course, the prediction depends on the chemical composition of the halo. In figure 3, we give the three illustrative cases of a He' dominated halo with mirror metal component consisting of: a) pure O' [figure 3a], b) pure Si' [figure 3b] and c) pure Fe' [figure 3c].

Figure 2c: Same as figure 2a, except, $\xi_{Fe'}/(\xi_{O'} + \xi_{Si'} + \xi_{Fe'}) = 0.04$. 
Figure 3a: Predicted CDMS/Ge energy spectrum: \( \epsilon(E_R) \times \frac{dR}{dE_R}|_{v_E=v_\odot} \) (where \( \epsilon(E_R) \) is the published detection efficiency) for \( \xi_{Si'} = \xi_{Fe'} = 0 \) and \( |\epsilon|\sqrt{\xi_{O'}} \) fixed by the positive DAMA/NaI annual modulation signal, \( R^1[(2-6)keVee] = 0.019 \) cpd/kg/keVee.

Figure 3b: Same as figure 3a, except that \( \xi_{O'} = \xi_{Fe'} = 0 \) and \( |\epsilon|\sqrt{\xi_{Si'}} \) is fixed by the positive DAMA/NaI annual modulation signal, \( R^1[(2-6)keVee] = 0.019 \) cpd/kg/keVee.
Figure 3c: Same as figure 3a, except that $\xi_{O'} = \xi_{Si'} = 0$ and $|\epsilon|\sqrt{\xi_{Fe'}}$ is fixed by the positive DAMA/NaI annual modulation signal, $R^1[(2-6)keVee] = 0.019$ cpd/kg/keVee.

As the figures show, the CDMS/Ge experiment is completely insensitive to $O'$, but does have some significant sensitivity to the $Si'$ and $Fe'$ components. Of course, the reason for this is clear: the heavier elements can transfer more momentum to the target nuclei and can therefore give more events.

Recall, a heavy $Si', Fe'$ component is expected from the non-negligible annual modulation in the $4-6$ keVee region observed in the DAMA/NaI experiment. Therefore, the current null results from the CDMS/Ge experiment does significantly constrain the mirror matter interpretation of the DAMA experiment. The null result of CDMS/Ge suggests a limit of $N < 3$ (at 95% C.L.) for their 52.6 kg-day sample (or equivalently, less than 0.057 cpd/kg). In figure 4 we combine this CDMS/Ge limit with the DAMA/NaI constraint, Eq.(24), to give the combined DAMA/NaI-CDMS/Ge allowed regions in the $v_{rot}, \xi_{Si'}/(\xi_{Si'} + \xi_{O'} + \xi_{Fe'})$ plane. Figure 4a assumes $\xi_{Fe'}/(\xi_{Si'} + \xi_{O'} + \xi_{Fe'}) = 0$, while figure 4b assumes $\xi_{Fe'}/(\xi_{Si'} + \xi_{O'} + \xi_{Fe'}) = 0.02$, and figure 4c assumes $\xi_{Fe'}/(\xi_{Si'} + \xi_{O'} + \xi_{Fe'}) = 0.04$. There is no allowed parameter space for $\xi_{Fe'}/(\xi_{Si'} + \xi_{O'} + \xi_{Fe'}) > 0.10$. 
Figure 4a: Region of parameter space (allowed region) consistent with the DAMA/NaI annual modulation signal, annual modulation energy spectrum constraint, Eq.(24) and also consistent with the null results of CDMS/Ge (at about 95% C.L.). This figure assumes $\xi_{Fe'} = 0$. The region to the right of the dashed curve corresponds to the DAMA/NaI lower limit, $R^1[(4-6)keVee]/R^1[(2-6)keVee] > 0.26$, already given in figure 2, while the region to the left of the solid curve is the CDMS/Ge constraint (predicted event rate < 0.057 cpd/kg, as discussed in text).
Figure 4b: Same as figure 4a, except with $\xi_{Fe'}/(\xi_{Si'} + \xi_{O'} + \xi_{Fe'}) = 0.02$.

Figure 4c: Same as figure 4a, except with $\xi_{Fe'}/(\xi_{Si'} + \xi_{O'} + \xi_{Fe'}) = 0.04$. 

DAMA/NaI - CDMS/Ge allowed region $[\xi_{Fe'}/(\xi_{Si'} + \xi_{O'} + \xi_{Fe'}) = 0.02]$

DAMA/NaI - CDMS/Ge allowed region $[\xi_{Fe'}/(\xi_{Si'} + \xi_{O'} + \xi_{Fe'}) = 0.04]$
Note that the allowed parameter space is fairly well defined. In fact, we would expect a positive signal from the CDMS/Ge experiment in the very near future, which we predict to be at recoil energies very close to threshold (certainly \( < 15 \) keV).

Very recently, the CDMS collaboration have presented new data\[30\] consisting of a raw exposure of about 93 kg-days for CDMS/Ge. Interestingly, they did obtain 1 event with a recoil energy of 10.5 keV passing their detection criteria. Furthermore, the background in the near threshold region \( (E_R < 15 \) keV) is expected to be much less than 1 event – given that the estimated background for the \( 10 \) keV \( < E_R < 100 \) keV region is just 0.4 events\[30\]. Of course, one shouldn’t take one event too seriously so we must wait for confirmation or non-confirmation in the near future. They also presented results for CDMS/Si which is also potentially sensitive to mirror matter-type dark matter. However, they have not published their over-all detection efficiency for CDMS/Si, so a quantitative analysis is not possible. However, assuming that the CDMS/Si experiment has the same over-all detection efficiency as the CDMS/Ge experiment (as given in figure 3 of ref.[19]), then we predict between 1-5 events for the exposure time of 74.5 live days for the allowed regions in figure 4.

5 Conclusion

In conclusion, we have re-analysed the mirror matter interpretation of the positive dark matter signal obtained in the DAMA/NaI experiment, taking into account the annual modulation spectrum constraint, Eq.(24). We have combined this with the null results from the CDMS/Ge experiment, to yield fairly well defined allowed regions of parameter space (figure 4). This favoured parameter space will be probed in the near future by the currently running DAMA/LIBRA and CDMS experiments. In particular, this interpretation of the DAMA/NaI experiment suggests that the CDMS/Ge (and CDMS/Si) experiment(s) should see a positive signal around the recoil energy threshold \( E_R < 15 \) keV in the near future.

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