Reconciling the positive DAMA annual modulation signal with the negative results of the CDMS II experiment

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We examine the recent CDMS II results in the context of the mirror matter interpretation of the DAMA/NaI experiment. We find that the favoured mirror matter interpretation of the DAMA/NaI experiment – a $\text{He}'/\text{H}'$ dominated halo with a small $\text{O}'$ component is fully consistent with the null results reported by CDMS II. While the CDMS II experiment is quite sensitive to a heavy $\text{Fe}'$ component, and may yet find a positive result, a more decisive test of mirror matter-type dark matter would require a lower threshold experiment using light target elements.

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The CDMS II experiment has recently announced first results from their cryogenic dark matter search in the Soudan Underground Laboratory[1]. With 19.4 kg-days of Ge effective exposure after cuts, and a threshold energy of 10 keV, they obtain strong limits on WIMP dark matter – ruling out a significant range of supersymmetric models. Furthermore, the CDMS II experiment is inconsistent with the impressive 6.3$\sigma$ DAMA annual modulation signal[2] if interpreted in terms of standard (spin independent) WIMPs. It is reasonable to conclude that the standard WIMP hypothesis is disfavoured by the experiments.

However, it has already been pointed out that a better explanation for the impressive DAMA/NaI annual modulation signal is given by mirror matter-type dark matter[3, 4]. The purpose of this note is to examine the latest CDMS results in the context of the mirror matter interpretation of the DAMA annual modulation signal.

Recall, mirror matter is predicted to exist if nature exhibits an exact unbroken mirror symmetry[5] (for reviews and more complete set of references, see Ref.[6]). For each type of ordinary particle (electron, quark, photon etc) there is a 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[5].

Mirror matter is a rather obvious candidate for the non-baryonic dark matter in the Universe because:

- It is well motivated from fundamental physics since it is required to exist if parity and time reversal symmetries are exact, unbroken symmetries of nature.
- It is necessarily dark and stable. Mirror baryons have the same lifetime as ordinary baryons and couple to mirror photons instead of ordinary photons.
- Mirror matter-type dark matter can provide a suitable framework for which to understand the large scale structure of the Universe[7].
- Recent observations from WMAP[8] and other experiments suggest that the cosmic abundance of non-baryonic dark matter is of the same order of magnitude as ordinary matter $\Omega_{\text{dark}} \sim \Omega_\text{b}$. A result which can naturally occur if dark matter is identified with mirror matter[9].

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

$$\mathcal{L} = \frac{\epsilon}{2} F^\mu_\nu F'^\nu_\mu$$

where $F^\mu_\nu$ ($F'^\mu_\nu$) is the field strength tensor for electromagnetism (mirror electromagnetism) $^2$. Photon-mirror photon mixing causes mirror charged particles to couple to

\[\text{Given the constraints of gauge invariance, renomalizability and mirror symmetry it turns out[5] that the only allowed non-gravitational interactions connecting the ordinary particles with the mirror particles are via photon-mirror photon kinetic mixing and via a Higgs-mirror Higgs quartic coupling, } \mathcal{L} = \lambda \phi^\dagger \phi \phi'^\dagger \phi'. \text{ If neutrinos have mass, then ordinary - mirror neutrino oscillations may also occur[10].} \]
ordinary photons with a small effective electric charge, $\epsilon e$ \cite{5, 11, 12}, leading to many interesting implications for astrophysics, particle physics and related fields\cite{13}.

One such interesting implication [of Eq.1] is that the DAMA/NaI experiment is sensitive to mirror matter-type dark matter\cite{3}. Halo mirror atoms can elastically scatter off ordinary atoms as a consequence of the photon-mirror photon kinetic mixing interaction, Eq.(1). The DAMA experiment is not particularly sensitive to very light dark matter particles such as mirror hydrogen and mirror helium. Impacts of these elements (typically) do not transfer enough energy to give a signal above the detection threshold\cite{3}. The next most abundant element is expected to be mirror oxygen (and nearby elements). A small mirror iron component is also possible. Interpreting the DAMA annual modulation signal in terms of $O'$, $Fe'$, we found that\cite{3}:

$$|\epsilon| \sqrt{\frac{\xi_{O'}}{0.10} + \frac{\xi_{Fe'}}{0.026}} \simeq 4.8_{-1.3}^{+1.0} \times 10^{-9}$$

where the errors denote a 3 sigma allowed range and $\xi_{A'} \equiv \rho_{A'}/(0.3 \text{ GeV/cm}^3)$ is the $A'$ proportion (by mass) of the halo dark matter.

In Ref.\cite{3} we found that a DAMA/NaI annual modulation signal dominated by the $Fe'$ component, is experimentally disfavoured for three independent reasons: a) it predicts a differential energy spectrum rate larger than the measured DAMA/NaI rate b) potentially leads to a significant diurnal effect c) should have been observed in the CDMS I experiment. Thus it is probable that the mirror oxygen component dominates the DAMA annual modulation signal, which from Eq.(2) means that $\xi_{O'} \gtrsim 4 \xi_{Fe'}$. In this case there are no significant problems with existing experiments.

If the DAMA signal is dominated by $O'$, then things depend on only one parameter, $\epsilon \sqrt{\xi_{O'}}$. This parameter is fixed from the annual modulation signal, Eq.(2), which means that the event rate (due to $O'$ interactions) can be predicted for other experiments. The prediction does depend on the assumed halo distribution. In our analysis we assume that the halo has the standard isothermal Maxwellian distribution

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

It is important to realize that the $v_0$ value for a particular halo component element, $A'$, depends on the chemical composition of the halo. In general\cite{4},

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

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) and $v_{rot} \simeq 220$ km/s is the local rotational velocity. The most abundant mirror elements should 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 $v_0$ values can be easily obtained from Eq.(4), taking into account that the light halo mirror atoms should be fully ionized:

$$v_0(A') = v_0(He') \sqrt{\frac{M_{He'}}{M_{A'}}} \approx \frac{220}{\sqrt{3}} \sqrt{\frac{M_{He'}}{M_{A'}}} \text{ km/s for He' dominated halo}$$
\[ v_0(A') = v_0(H') \sqrt{\frac{M_{H'}}{M_A}} \approx \frac{220}{\sqrt{2}} \sqrt{\frac{M_{H'}}{M_A}} \text{ km/s for } H' \text{ dominated halo.} \quad (5) \]

Mirror BBN\cite{7} suggests that \( He' \) dominates over \( H' \), but we will consider both limiting cases in this paper.

It is a straightforward exercise to work out the predicted event rate for the CDMS II/Ge and CDMS II/Si experiments. [See Ref.\cite{3} for details of the cross section, form factors and rate equations used]. In figure 1 we give the predicted event rate for the CDMS II/Ge experiment taking into account the published detection efficiency (figure 3 of Ref.\cite{1}). Figure 2 is the corresponding figure for the CDMS II/Si experiment (assuming the same detection efficiency). As the figures show, the event rate is predicted to be very low. For the CDMS II/Ge experiment the predicted event rate is just 1 event per \( 2.6 \times 10^6 \) kg-days for \( He' \) dominant halo and 1 event per \( 5 \times 10^{12} \) kg-days if \( H' \) dominates the halo. Given that CDMS II has only 52.6 kg-day raw exposure in Ge, this implies a predicted number of events of just \( 2 \times 10^{-5} \) (assuming \( He' \) dominant halo) and even less if \( H' \) dominates the mass of the halo. Clearly this prediction is nicely consistent with the null result of CDMS II/Ge. In the case of the CDMS II/Si experiment, the predicted event rate (due to \( O' \) interactions) is 1 event per \( 710 \) kg-days (for \( He' \) dominated halo) and 1 event per \( 200,000 \) kg-days (for \( H' \) dominated halo). CDMS II/Si currently has about 20 kg-days of raw exposure in Si, so CDMS II/Si is also not sensitive to \( O' \) dark matter. Overall, the CDMS II experiment is not sensitive to \( O' \) dark matter – certainly many orders of magnitude less sensitive than the DAMA/NaI experiment.

![Figure 1](image_url)

Figure 1: Predicted differential event rate, \( dR/dE_R \), (binned into 10 keV bins) due to \( O' \) dark matter with \( \epsilon_{\sqrt{\xi_{O'}}} = 4.8 \times 10^{-9} \) (DAMA/NaI annual modulation best fit) for the CDMS II/Ge experiment. The solid line corresponds to a standard halo model with \( He' \) dominated halo while the dashed line assumes a \( H' \) dominated halo.
In the case of standard spin independent WIMPs, the CDMS II experiment is more sensitive than the DAMA/NaI experiment. However, as we have discussed above, this is clearly not the case for $O'$-type dark matter (with dominant $He'/H'$ component). The diverse behaviour of the two types of dark matter candidate has to do with their basic differences:

- The differential cross section for mirror matter-type dark matter is inversely proportional to the square of the recoil energy, while that for WIMPs is energy independent (excepting the energy dependence of the form factors).
- For $O'$-type dark matter in an $He'/H'$ dominated halo, $v_0(O') \ll 220$ km/s, while the characteristic velocity of WIMPs are assumed to be approximately 220 km/s.
- The mass of $O'$ is only 15 GeV, while WIMPs are typically constrained from W,Z decays to be heavier than 30 – 45 GeV (depending on the model).

These three differences mean that experiments with low threshold energy and light target elements are much more sensitive (to $O'$-type dark matter) than experiments with higher threshold energy and/or heavy target elements. In the case of DAMA/NaI, the event rate for mirror matter-type dark matter is dominated by interactions with the light $Na$ component. The actual threshold energy of 6.7 keV (for $Na$), implies a threshold impact velocity of 290 km/s. In the case of CDMS II/Ge, the threshold energy of 10 keV and heavy Ge target gives a threshold impact velocity of 450 km/s (see Ref.[14] for a table of threshold velocities for the various experiments). Given the low value of $v_0(O')$ [$v_0(O') = \frac{110}{\sqrt{3}}$ km/s (\frac{55}{\sqrt{2}} km/s) for $He' (H')$ dominated halo] the number of $O'$ atoms with impact velocity above threshold is clearly much lower for CDMS II/Ge.
compared with DAMA/NaI. Note that the Edelweiss I/Ge and Zeplin I/Xe experiments are even less sensitive than CDMS II/Ge because the threshold impact velocity of those experiments is even higher[14].

Although the CDMS II experiment is relatively insensitive to impacts of \( O' \), it is much more sensitive to impacts of heavier mirror atoms. If we assumed that the DAMA/NaI experiment were due to \( Fe' \) interactions in a \( He'/H' \) dominated halo, then we would have predicted around 30 events (roughly independently on whether \( H' \) or \( He' \) dominates the mass of the halo) for the CDMS II 52.6 kg-day Ge raw exposure. This is clearly excluded by the data which failed to find any events. Evidently \( Fe' \) can only be a small component of the halo, with energy density much less than \( O' \). Assuming the standard halo model, we find that \( \xi_{Fe'} \sim \xi_{O'}/40 \) at 90% C.L. (independently of whether \( He' \) or \( H' \) dominates the mass of the halo). Clearly, future CDMS data may well find a positive signal – corresponding to an \( Fe' \) component – which should be there at some level.

In conclusion, we have examined the recent CDMS II results in the context of the mirror matter interpretation of the DAMA/NaI experiment. The favoured mirror matter interpretation of the DAMA/NaI experiment – a \( He'/H' \) dominated halo with a small \( O' \) component is fully consistent with the null results reported by CDMS II. While the CDMS II experiment is quite sensitive to a heavy \( Fe' \) component, and may yet find a positive result, a more decisive test of mirror matter-type dark matter would require a lower threshold experiment using light target elements (such as DAMA/LIBRA and CRESST II).

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References

[1] D. S. Akerib et al. (CDMS Collaboration), astro-ph/0405033.

[2] R. Bernabei et al. (DAMA Collaboration), Phys. Lett. B480, 23 (2000); Riv. Nuovo Cimento. 26, 1 (2003) [astro-ph/0307403].

[3] R. Foot, Phys. Rev. D69, 036001 (2004) [hep-ph/0308254].

[4] R. Foot, astro-ph/0403043.

[5] R. Foot, H. Lew and R. R. Volkas, Phys. Lett. B272, 67 (1991). The mirror matter idea was earlier discussed, prior to the advent of the standard model, in: T. D. Lee and C. N. Yang, Phys. Rev. 104, 256 (1956); I. Kobzarev, L. Okun and I. Pomeranchuk, Sov. J. Nucl. Phys. 3, 837 (1966); M. Pavsic, Int. J. Theor. Phys. 9, 229 (1974).

[6] R. Foot, hep-ph/0207175; R. Foot, Acta Phys. Pol B32, 2253 (2001) [astro-ph/0102294]; A. Yu. Ignatiev and R. R. Volkas, Talk given at the Australian
Institute of Physics Congress, July 2002 [hep-ph/0306120]; Z. Silagadze, Acta Phys. Pol. B32, 99 (2001) [hep-ph/0002255]; R. Foot, Shadowlands: Quest for mirror matter in the Universe, Universal Publishers, FL, 2002.

[7] Z. Berezhiani, D. Comelli and F. L. Villante, Phys. Lett. B503, 362 (2001) [hep-ph/0008105]; A. Yu. Ignatiev and R. R. Volkas, Phys. Rev. D68 023518 (2003) [hep-ph/0304260]. For pioneering work, see also S. I. Blinnikov and M. Yu. Khlopov, Sov. J. Nucl. Phys. 36, 472 (1982); Sov. Astron. 27, 371 (1983).

[8] D. N. Spergel et al. (WMAP Collaboration), Ap. J. Suppl. 148, 175 (2003) [astro-ph/0302209].

[9] R. Foot and R. R. Volkas, Phys. Rev. D68, 021304 (2003) [hep-ph/0304261]; see also L. Bento and Z. Berezhiani, hep-ph/0111116.

[10] R. Foot, H. Lew and R. R. Volkas, Mod. Phys. Lett. A7, 2567 (1992); R. Foot, Mod. Phys. Lett. A9, 169 (1994) [hep-ph/9402241]; R. Foot and R. R. Volkas, Phys. Rev. D52, 6595 (1995) [hep-ph/9505359].

[11] B. Holdom, Phys. Lett. B166, 196 (1986).

[12] R. Foot, A. Yu. Ignatiev and R. R. Volkas, Phys. Lett. B503, 355 (2001) [astro-ph/0011156].

[13] S. L. Glashow, ibid. B167, 35 (1986); E. D. Carlson and S. L. Glashow, ibid. B193, 168 (1987); R. Foot and S. Gnenenko, ibid. B480, 171 (2000) [hep-ph/0003278]; R. Foot and R. R. Volkas, ibid. B 517, 13 (2001) [hep-ph/0108051]; R. Foot, Acta Phys. Polon. B32, 3133 (2001) [hep-ph/0107132]; R. Foot and T. L. Yoon, ibid. B33, 1979 (2002) [astro-ph/0203152]; R. Foot and S. Mitra, Phys. Rev. D66, 061301 (2002) [hep-ph/0204256]; Astropart. Phys. 19, 739 (2003) [astro-ph/0211067]; Phys. Lett. B558, 9 (2003) [astro-ph/0301229]; Phys. Lett. A315, 178 (2003) [cond-mat/0306561]; Phys. Rev. D68, 071901 (2003) [hep-ph/0306228]; A. Badertscher et al., hep-ex/0311031; Z. Silagadze, astro-ph/0311337; R. Foot and Z. K. Silagadze, astro-ph/0404515.

[14] R. Foot, astro-ph/0309330.