

Mirror dark matter*

R. Foot**

School of Physics, University of Melbourne, Victoria 3010 Australia

*** E-mail: rfoot@unimelb.edu.au*

A mirror sector of particles and forces provides a simple explanation of the inferred dark matter of the Universe. The status of this theory is reviewed - with emphasis on how the theory explains the impressive DAMA/NaI annual modulation signal, whilst also being consistent with the null results of the other direct detection experiments.

There is strong evidence for non-baryonic dark matter in the Universe from observations of flat rotation curves in spiral galaxies, from precision measurements of the CMB and from the DAMA/NaI annual modulation signal. The standard model of particle physics has no candidate particles. Therefore new particle physics is suggested.

There are four most basic requirements for a dark matter candidate:

- Massive - The elementary particle(s) comprising the non-baryonic dark matter need to have mass.
- Dark - The dark matter particles couple very weakly to ordinary photons (e.g. electrically neutral particles).
- Stable - The lifetime should be greater than about 10 billion years.
- Abundance - $\Omega_{dark} \approx 5\Omega_b$ (inferred from WMAP CMB observations¹).

It is not so easy to get suitable candidates from particle physics satisfying these four basic requirements. A popular solution is to hypothesize new neutral particles which are weakly interacting (WIMPs), but this doesn't necessarily make them stable. In fact, the most natural life-time of a hypothetically weakly interacting particle is very short:

$$\tau(wimp) \sim \frac{M_W^4}{g^4 M_{wimp}^5} \sim 10^{-24} \text{ seconds} \quad - \quad \text{if } M_{wimp} \sim M_Z . \quad (1)$$

This is about 41 orders of magnitude too short lived! Of course there is a trivial solution - which is to invent a symmetry to kinematically forbid the particle to decay, but this is ugly because it is ad hoc. The proton and electron, for example,

*Talk given in the Festschrift in honour of G. C. Joshi and B. H. J. McKellar, November 2006.

are not stabilized by any such ad hoc symmetry^a. It is reasonable to suppose that the dark matter particles, like the proton and electron, will also have a good reason for their stability. On the other hand, we also know that the standard model works very well. There is no evidence for anything new (except for neutrino masses). For example, precision electroweak tests are all nicely consistent with no new physics.

A simple way to introduce dark matter candidates which are naturally dark, stable, massive and don't modify standard model physics is to introduce a mirror sector of particles and forces.² For every standard model particle there exists a mirror partner^b, which we shall denote with a prime ('). The interactions of the mirror particles have the same form as the standard particles, so that the Lagrangian is essentially doubled:

$$\mathcal{L} = \mathcal{L}_{SM}(e, d, u, \gamma, \dots) + \mathcal{L}_{SM}(e', d', u', \gamma', \dots) \quad (2)$$

At this stage, the two sectors are essentially decoupled from each other except via gravity (although we will discuss the possible ways in which the two sectors can interact with each other in a moment). In such a theory, the mirror baryons are naturally dark, stable and massive and are therefore, a priori, excellent candidates for dark matter. The theory exhibits a gauge symmetry which is $G_{SM} \otimes G_{SM}$ (where $G_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ is the standard model gauge symmetry).

One can define a discrete symmetry interchanging ordinary and mirror particles, which can be interpreted as space-time parity symmetry ($x \rightarrow -x$) if the roles of left and right chiral fields are interchanged in the mirror sector. Because of this geometrical interpretation, one cannot regard this discrete symmetry as ad hoc in any sense.

An obvious question is: can ordinary and mirror particles interact with each other non-gravitationally? The answer is YES - but only two terms are consistent with renormalizability and symmetry:²

$$\mathcal{L}_{mix} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \lambda \phi^\dagger \phi \phi'^\dagger \phi' , \quad (3)$$

where $F_{\mu\nu}$ ($F'_{\mu\nu}$) is the ordinary (mirror) $U(1)$ gauge boson field strength tensor and ϕ (ϕ') is the electroweak Higgs (mirror Higgs) field. These two terms are very important, because they lead to ways to experimentally test the idea.

With the above Higgs - mirror Higgs quartic coupling term included, the full Higgs potential of the model has three parameters. Minimizing this potential, one finds that there are two possible vacuum solutions (with each solution holding for a range of parameters): $\langle \phi \rangle = \langle \phi' \rangle \simeq 174$ GeV (unbroken mirror symmetry) and $\langle \phi \rangle \simeq 174$ GeV, $\langle \phi' \rangle = 0$ (spontaneously broken mirror symmetry^c). While both

^aProtons and electrons are stabilized by baryon and lepton number $U(1)$ global symmetries which are not imposed, but are accidental symmetries of the standard model. These symmetries cannot be broken by any renormalizable term consistent with the gauge symmetries in the standard model.

^bFor a more comprehensive review, see. e.g. ref.³.

^cMirror QCD effects eventually break $SU(2) \times U(1)$ in the mirror sector leading to a small, but non-zero VEV for ϕ' in the spontaneously broken case. See Ref.⁴ for details.

vacuum solutions are phenomenologically viable, we shall henceforth assume that the mirror symmetry is unbroken, because that case seems more interesting from a dark matter perspective. In the unbroken mirror symmetry case the mass and interactions of the mirror particles are exactly the same as the ordinary particles (except for the interchange of left and right).

Is mirror matter too much like ordinary matter to account for the non-baryonic dark matter in the Universe? After all, ordinary and dark matter have some different properties:

- Dark matter is (roughly) spherically distributed in spiral galaxies, which is in sharp contrast to ordinary matter which has collapsed onto the disk.
- $\Omega_{dark} \neq \Omega_b$ but $\Omega_{dark} \approx 5\Omega_b$.
- Big Bang Nucleosynthesis (BBN) works very well without any extra energy density from a mirror sector.
- Large scale structure formation should begin prior to ordinary photon decoupling.

Clearly there is no ‘macroscopic’ symmetry. But this doesn’t preclude the possibility of exactly symmetric microscopic physics. Why? Because the initial conditions in the Universe might be different in the two sectors. In particular, if in the early Universe, the temperature of the mirror particles (T') were significantly less than the ordinary particles (T) then:

- Ordinary BBN is not significantly modified provided $T' \lesssim 0.5T$.
- $\Omega_{dark} \neq \Omega_b$ since baryogenesis mechanisms typically depend on temperature^d.
- Structure formation in the mirror sector can start before ordinary photon decoupling because mirror photon decoupling occurs earlier if $T' < T$.⁷ Detailed studies⁸ find that for $T' \lesssim 0.2T$ successful large scale structure follows. This dark matter candidate is also nicely consistent with CMB measurements.⁹
- Furthermore, BBN in the mirror sector is quite different since mirror BBN occurs earlier if $T' < T$. In fact, because of the larger expansion rate at earlier times we would expect that the He'/H' ratio be much larger than the ratio of He/H in the Universe. This would change the way mirror matter evolves on short scales c.f. ordinary matter. Maybe this can explain why mirror matter hasn’t yet collapsed onto the disk.¹⁰

Ok, so mirror matter can plausibly explain the non-baryonic dark matter inferred to exist in the Universe. Can it really be experimentally tested though?

^dThe fact that $\Omega_{dark} \neq \Omega_b$ but $\Omega_{dark} \sim \Omega_b$ is suggestive of some similarity between the ordinary and dark matter particle properties, which might be explained within the mirror dark matter context by having exactly symmetric microscopic physics and asymmetric temperatures. For some specific models in this direction, see ref.^{5,6}.

The Higgs mixing term will impact on the properties of the standard model Higgs.^{11,12} This may be tested if a scalar is found in experiments, e.g. at the forthcoming LHC experiment. More interesting, at the moment, is the $\epsilon F^{\mu\nu} F'_{\mu\nu}$ term. This interaction leads to kinetic mixing of the ordinary photon with the mirror photon, which in turn leads to orthopositronium - mirror orthopositronium oscillations¹³ (see also¹⁴). Null results of current experiments imply¹⁵ $\epsilon < 5 \times 10^{-7}$. Another consequence of the $\epsilon F^{\mu\nu} F'_{\mu\nu}$ term is that it will lead to elastic (Rutherford) scattering of mirror baryons off ordinary baryons, since the mirror proton effectively couples to ordinary photons with electric charge ϵe . This means that conventional dark matter detection experiments currently searching for WIMPs can also search for mirror dark matter!¹⁶ The DAMA/NaI experiment already claims direct detection of dark matter.¹⁷ Can mirror dark matter explain that experiment?

The interaction rate in an experiment such as DAMA/NaI has the general form:

$$\frac{dR}{dE_R} = \sum_{A'} N_T n_{A'} \int_{v'_{min}(E_R)}^{\infty} \frac{d\sigma}{dE_R} \frac{f(v', v_E)}{k} |v'| d^3v' \quad (4)$$

where N_T is the number of target atoms per kg of detector, $n_{A'}$ is the galactic halo number density of dark matter particles labeled as A' . We include a sum allowing for more than one type of dark matter particle. In the above equation $f(v', v_E)/k$ is the velocity distribution of the dark matter particles, A' , and v_E is the Earth's velocity relative to the galaxy. Also, $v'_{min}(E_R)$ is the minimum velocity for which a dark matter particle of mass $M_{A'}$ impacting on a target atom of mass M_A can produce a recoil of energy E_R for the target atom. This minimum velocity satisfies the kinematic relation:

$$v'_{min}(E_R) = \sqrt{\frac{(M_A + M_{A'})^2 E_R}{2M_A M_{A'}^2}} \quad (5)$$

The DAMA experiment eliminates the background by using the annual modulation signature. The idea¹⁸ is very simple. The rate, Eq.4, must vary periodically since it depends on the Earth's velocity, v_E , which modulates due to the Earth's motion around the Sun. That is,

$$R(v_E) = R(v_{\odot}) + \left(\frac{\partial R}{\partial v_E} \right)_{v_{\odot}} \Delta v_E \cos \omega(t - t_0) \quad (6)$$

where $\Delta v_E \simeq 15$ km/s, $\omega \equiv 2\pi/T$ ($T = 1$ year) and $t_0 = 152.5$ days (from astronomical data). The phase and period are both predicted! This gives a strong systematic check on their results. Such an annual modulation was found¹⁷ at the 6.3σ Confidence level, with T, t_0 measured to be:

$$\begin{aligned} T &= 1.00 \pm 0.01 \text{ year} \\ t_0 &= 140 \pm 22 \text{ days} \end{aligned} \quad (7)$$

Clearly, both the period and phase are consistent with the theoretical expectations of halo dark matter.

The signal occurs in a definite low energy range from 6 keVee down to the experimental threshold of 2 keVee^e. No annual modulation was found for $E_R > 6$ keVee. Given that the mean velocity of halo dark matter particles relative to the Earth is of order the local rotational velocity (~ 300 km/s), this suggests a mass for the (cold) dark matter particles roughly of order 20 GeV, since:

$$E = \frac{1}{2}mv^2 \simeq \frac{m}{20 \text{ GeV}} \left(\frac{v}{300 \text{ km/s}} \right)^2 10 \text{ keV}. \quad (8)$$

Dark matter particles with mass larger than about 60 GeV would give a signal above the 6 keVee region (no such signal was observed in the DAMA experiment). On the other hand, dark matter particles with mass less than about 5 GeV do not have enough energy to produce a signal in the 4-6 keVee energy region - which would be contrary to the DAMA results. Importantly, the mass region sensitive to the DAMA experiment coincides with that predicted by mirror dark matter, since mirror dark matter predicts a spectrum of dark matter elements ranging in mass from hydrogen to iron. That is, with mass $\text{GeV} \lesssim M_{A'} \lesssim 55 \text{ GeV}$. A detailed analysis¹⁶ confirms that mirror dark matter can fit the DAMA experimental data and the required value for ϵ is $\epsilon \sim 10^{-9}$. This fit to the annual modulation signal is given in **figure 1**.

Interestingly, a mirror sector interacting with the ordinary particles with $\epsilon \sim 10^{-9}$ has many other interesting applications (see e.g. ref.^{19,20}). It also consistent with the Laboratory (orthopositronium) bound as well as BBN constraints.²¹

What about the null results of the other direct detection experiments, such as the CDMS, Zeplin, Edelweiss experiments? For any model which explains the DAMA/NaI annual modulation signal, the corresponding rate for the other direct detection experiments can be predicted. These null results do seem to disfavour the WIMP interpretation of the DAMA experiment. However it turns out that they do not, at present, disfavour the mirror dark matter interpretation. Why? because these other experiments are typically all higher threshold experiments with heavier target elements than Na (which, in the mirror matter interpretation, dominates the DAMA/NaI signal) and mirror dark matter has three key features which make it less sensitive (than WIMPs) to higher threshold experiments.

- Mirror dark matter is relatively light $M_H \leq M_{A'} \leq M_{Fe}$.
- The Rutherford cross section has the form:

$$\frac{d\sigma}{dE_R} \propto \frac{1}{E_R^2}$$

while for WIMPs it is E_R independent (excepting the energy dependence of the form factors).

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

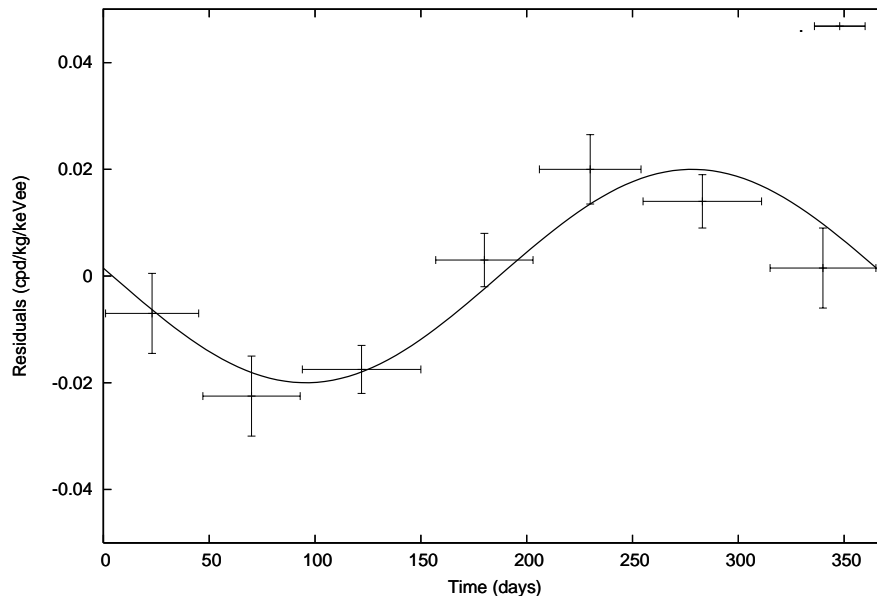


Fig. 1. DAMA/NaI annual modulation signal (taking data from ref.¹⁷) together with the mirror matter prediction. Note that the initial time in this figure is August 7th.

- Mirror particles interact with each other. This implies that the Halo particles are in local thermodynamic equilibrium, so that e.g. $T = \frac{1}{2}M_{H'}\overline{v_{H'}^2} = \frac{1}{2}M_{O'}\overline{v_{O'}^2}$ (≈ 300 eV assuming the standard assumptions of an isothermal halo in hydrostatic equilibrium³). Thus heavier elements have smaller mean velocities.

To summarize, having a mirror sector is a simple way to explain the inferred dark matter of the Universe. There is experimental support for this particular dark matter hypothesis, coming from the positive DAMA annual modulation signal. We must await future experiments to see if this explanation is the correct hypothesis.

Acknowledgements: This work was supported by the Australian Research Council.

References

1. D. N. Spergel *et al.*, (WMAP Collaboration), *Astrophys. J. Suppl.* 148, 175 (2003) [astro-ph/0302209].
2. R. Foot, H. Lew and R. R. Volkas, *Phys. Lett. B*272, 67 (1991). The idea that a mirror sector might exist was discussed earlier, prior to the advent of the standard model of particle physics, 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). The first application to non-baryonic dark matter was given in: S. I. Blinnikov and M. Yu. Khlopov, Sov. J. Nucl. Phys. 36, 472 (1982); Sov. Astron. 27, 371 (1983).
3. R. Foot, Int. J. Mod. Phys. D13, 2161 (2004) [astro-ph/0407623].
 4. R. Foot and H. Lew, hep-ph/9411390; R. Foot, H. Lew and R. R. Volkas, JHEP 0007, 032 (2000) [hep-ph/0006027].
 5. L. Bento and Z. Berezhiani, Phys. Rev. Lett. 87, 231304 (2001) [hep-ph/0107281]; hep-ph/0111116.
 6. R. Volkas and R. Foot, Phys. Rev. D68, 021304 (2003) [hep-ph/0304261]; Phys. Rev. D69, 123510 (2004) [hep-ph/0402267].
 7. Z. Berezhiani, D. Comelli and F. L. Villante, Phys. Lett. B503, 362 (2001) [hep-ph/0008105].
 8. A. Yu. Ignatiev and R. R. Volkas, Phys. Rev. D68, 023518 (2003) [hep-ph/0304260].
 9. Z. Berezhiani *et al.*, Int. J. Mod. Phys. D14, 107 (2005) [astro-ph/0312605]; P. Ciarcelluti, astro-ph/0312607; P. Ciarcelluti, Int. J. Mod. Phys. D14, 187 (2005) [astro-ph/0409630]; Int. J. Mod. Phys. D14, 223 (2005) [astro-ph/0409633].
 10. R. Foot and R. R. Volkas, Phys. Rev. D70, 123508 (2004) [astro-ph/0407522].
 11. R. Foot, H. Lew and R. R. Volkas, Mod. Phys. Lett. A7, 2567 (1992).
 12. A. Yu. Ignatiev and R. R. Volkas, Phys. Lett. B487, 294 (2000) [hep-ph/0005238].
 13. S. L. Glashow, Phys. Lett. B167, 35 (1986).
 14. R. Foot and S. N. Gninenko, Phys. Lett. B480, 171 (2000) [hep-ph/0003278].
 15. R. Foot, Int. J. Mod. Phys. A19, 3807 (2004) [astro-ph/0309330].
 16. R. Foot, Phys. Rev. D69, 036001 (2004) [hep-ph/0308254]; R. Foot, Mod. Phys. Lett. A19, 1841 (2004) [astro-ph/0405362]; R. Foot, Phys. Rev. D74, 023514 (2006) [astro-ph/0510705].
 17. R. Bernabei *et al.*, (DAMA Collaboration), Riv. Nuovo Cimento. 26, 1 (2003) [astro-ph/0307403]; Int. J. Mod. Phys. D13, 2127 (2004) and references there-in.
 18. A. K. Drukier, K. Freese and D. N. Spergel, Phys. Rev. D33, 3495 (1986); K. Freese, J. A. Frieman and A. Gould, Phys. Rev. D37, 3388 (1988).
 19. R. Foot and S. Mitra, Astropart. Phys. 19, 739 (2003) [astro-ph/0211067].
 20. R. Foot and Z. K. Silagadze, Int. J. Mod. Phys. D14, 143 (2005) [astro-ph/0404515].
 21. E. D. Carlson and S. L. Glashow, Phys. Lett. B193, 168 (1987).