Early Universe cosmology in the light of the mirror dark matter interpretation of the DAMA/Libra signal

P. Ciarcelluti
IFPA, Département AGO, Université de Liège, 4000 Liège, Belgium

R. Foot
School of Physics, University of Melbourne, 3010 Australia.

Mirror dark matter provides a simple framework for which to explain the DAMA/Libra annual modulation signal consistently with the null results of the other direct detection experiments. The simplest possibility involves ordinary matter interacting with mirror dark matter via photon-mirror photon kinetic mixing of strength $\epsilon \sim 10^{-9}$. We confirm that photon-mirror photon mixing of this magnitude is consistent with constraints from ordinary Big Bang nucleosynthesis as well as the more stringent constraints from cosmic microwave background measurements and large scale structure considerations.
A mirror sector of particles and forces can be well motivated from fundamental considerations in particle physics, since its existence allows for improper Lorentz symmetries, such as space-time parity and time reversal, to be exact unbroken microscopic symmetries[1]. The idea is to introduce a hidden (mirror) sector of particles and forces, exactly duplicating the known particles and forces, except that in the mirror sector the roles of left and right chiral fields are interchanged. We shall denote the mirror particles with a prime (′). In such a theory, the mirror protons and nuclei are naturally dark, stable and massive, and provide an excellent candidate for dark matter consistent with all observations and experiments[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. For a review, see e.g. ref.[17]. Dark matter from a generic hidden sector is also possible, see e.g. ref.[18] for a recent study.

It has been shown in ref.[19], up-dating earlier studies[20], that the mirror dark matter candidate is capable of explaining the positive dark matter signal obtained in the DAMA/Libra experiment[21], while also being consistent with the null results of the other direct detection experiments. The simplest possibility sees the mirror particles coupling to the ordinary particles via renormalizable photon-mirror photon kinetic mixing[22] (such mixing can also be induced radiatively if heavy particles exist charged under both ordinary and mirror
\[ U(1)_{em} \] [23]):

\[ \mathcal{L}_{\text{mix}} = \frac{\epsilon}{2} F^\mu_\nu F'^{\mu}_\nu \] (1)

where \( F^\mu_\nu = \partial^\mu A^\nu - \partial^\nu A^\mu \) and \( F'^\mu_\nu = \partial^\mu A'^\nu - \partial^\nu A'^\mu \). This mixing enables mirror charged particles to couple to ordinary photons with charge \( e \epsilon q \), where \( q = -1 \) for \( e' \), \( q = +1 \) for \( p' \) etc. The mirror dark matter interpretation of the DAMA/Libra experiment requires[19] \( \epsilon \sim 10^{-9} \), which is consistent with laboratory and astrophysical constraints[24].

The purpose of this note is to study the implications of such mixing for the early Universe. In particular, we will check that this kinetic mixing is consistent with constraints from ordinary Big Bang nucleosynthesis (BBN) as well as more stringent constraints from cosmic microwave background (CMB) and large scale structure (LSS) considerations.

In the mirror dark matter scenario, it is assumed there is a temperature asymmetry \( (T' < T) \) between the ordinary and mirror radiation sectors in the early Universe due to some physics at early times (for specific models, see e.g. [25]). This is required in order to explain ordinary BBN, which suggests that \( T'/T \lesssim 0.6 \). In addition, several analyses[7, 8] based on numerical simulations of CMB and LSS suggest \( T'/T \sim 0.3 \). However, if photon-mirror photon kinetic mixing exists, it can potentially thermally populate the mirror sector. For example, Carlson and Glashow[26] derived the approximate bound of \( \epsilon \lesssim 3 \times 10^{-8} \) from requiring that the mirror sector does not come into thermal equilibrium with the ordinary sector, prior to BBN. The inferred value of \( \epsilon \sim 10^{-9} \) is consistent with this bound, so that we expect the kinetic mixing to populate the mirror sector, but with \( T' < T \). Assuming an effective initial condition \( T' \ll T \), we can estimate the evolution of \( T'/T \) in the early Universe as a function of \( \epsilon \), and thereby check the compatibility of the theory with the BBN and CMB/LSS constraints on \( T'/T \).

Photon-mirror photon kinetic mixing can populate the mirror sector in the early Universe via the process \( e^+e^- \rightarrow e'^+e'^- \). This leads to the generation of energy density in the
mirror sector of:

$$\frac{\partial \rho'}{\partial t} = n_{e^+} n_{e^-} \langle \sigma v_{Mol} E \rangle$$

(2)

where $\mathcal{E}$ is the energy transferred in the process, $v_{mol}$ is the Møller velocity (see e.g. ref. [27]), and $n_{e^-} \simeq n_{e^+} \simeq \frac{2}{gT^3}$. It is useful to consider the quantity: $\rho'/\rho$, in order to cancel the time dependence due to the expansion of the Universe [recall $\rho = \frac{\pi^2}{30} gT^4$]. Using the time temperature relation:

$$t = 0.3 g^{-1/2} M_{Pl}$$

(3)

with $g = 10.75$ and $M_{Pl} \simeq 1.22 \times 10^{22}$ MeV, we find that:

$$\frac{d(\rho'/\rho)}{dT} = \frac{-n_{e^-} n_{e^+} \langle \sigma v_{Mol} E \rangle}{\pi^2 gT^4/30} \frac{0.6 M_{Pl}}{\sqrt{g} T^3}.$$  

(4)

Let us focus on $\langle \sigma v_{Mol} E \rangle$. This quantity is:

$$\langle \sigma v_{Mol} E \rangle = \int \frac{\sigma v_{Mol}(E_1 + E_2)}{1 + e^{E_1/T}} \frac{1}{1 + e^{E_2/T}} \frac{1}{d^3 p_1 d^3 p_2}$$

(5)

where we have neglected Pauli blocking effects. If one makes the simplifying assumption of using Maxwellian statistics instead of Fermi-Dirac statistics then one can show (see appendix) that in the massless electron limit:

$$\langle \sigma v_{Mol} E \rangle = \frac{2\pi^2 \alpha^2 e^2}{3T},$$

(6)

and Eq.(4) reduces to:

$$\frac{d(\rho'/\rho)}{dT} = -\frac{A}{T^2}$$

(7)

where

$$A = \frac{27\zeta(3)^2 \alpha^2 e^2 M_{Pl}}{\pi^5 g \sqrt{g}}.$$  

(8)

Note that the $e'\pm$ will thermalize with $\gamma'$. However, because most of the $e'\pm$ are produced in the low $T' \lesssim 5$ MeV region, mirror weak interactions are too weak to significantly populate the $\nu'_{e,\mu,\tau}$ [i.e. one can easily verify a posteriori that the evolution of $T'/T$ for the parameter space of interest is such that $G_F^2 T'^5 \ll \sqrt{g} T^2 / 0.3 M_{Pl}$]. Thus to a good approximation the radiation content of the mirror sector consists of $e'^\pm$, $\gamma'$ leading to $g' = 11/2$ and hence $\rho'/\rho = (g'/g)(T'^4/T^4)$, with $g'/g \approx 22/43$. 

3
Eq.(7) has the analytic solution:

\[
\frac{T'}{T} = \left( \frac{g}{g' A} \right)^{1/4} \left[ \frac{1}{T} - \frac{1}{T_i} \right]^{1/4}
\]

(9)

where we have assumed the initial condition \( T' = 0 \) at \( T = T_i \).

Let us now include the effects of the electron mass. With non-zero electron mass, the evolution of \( T'/T \) cannot be solved analytically, but Eq.(4) can be solved numerically. Note that the number density is:

\[
n_{e^-} = \frac{1}{\pi^2} \int_{m_e}^{\infty} \frac{\sqrt{E^2 - m_e^2 E}}{1 + \exp(E/T)} \, dE
\]

(10)

and, as we discuss in the appendix,

\[
\langle \sigma v_{M\alpha} E \rangle = \frac{1}{8m_e^2 T^2 R_0^2 (m_e/T)} \int_{4m_e^2}^{\infty} ds \sigma(s - 4m_e^2) \sqrt{s} \int_{\sqrt{s}}^{\infty} dE_+ e^{-E+/T} E_+ \sqrt{\frac{E_+^2}{s} - 1}
\]

(11)

where the cross section is:

\[
\sigma = \frac{4\pi}{3} \alpha^2 \epsilon^2 \frac{1}{s^3} (s + 2m_e^2)^2.
\]

(12)

Numerically solving Eq.(4) with the above inputs (i.e. numerically solving the integrals Eq.(10) and Eq.(11) at each temperature step), we find that\(^3\)

\[
\epsilon \approx 8.5 \times 10^{-10} \left( \frac{x_f 0.3}{0.3} \right)^2
\]

(13)

where \( x_f \) is the final value \( (T \to 0) \) of \( x = T'/T \). In figure 1, we plot the evolution of \( T'/T \), for \( \epsilon = 8.5 \times 10^{-10} \).

In deriving this result we have made several simplifying approximations. The most significant of these are the following: a) Using Maxwellian statistics instead of Fermi-Dirac statistics to simplify the estimate of \( \langle \sigma v_{M\alpha} E \rangle \). Using Fermi-Dirac statistics should decrease the interaction rate by around 8% as discussed in the appendix. b) We have neglected Pauli blocking effects. Including Pauli blocking effects will slightly reduce the interaction rate since some of the \( e^{\pm} \) states are filled thereby reducing the available phase space. We estimate that the effect of the reduction of the interaction rate due to Pauli blocking will be around \( \lesssim 10\% \). c) We have assumed that negligible \( \nu'_{e,\mu,\tau} \) are produced via mirror weak interactions from the \( e^{\pm} \). Production of \( \nu'_{e,\mu,\tau} \) will slightly decrease the \( T'/T \) ratio. The effect of this is equivalent to reducing the interaction rate by around \( \lesssim 10\% \). Taking these effects into account, we revise Eq.(13) to:

\[
\epsilon = (1.0 \pm 0.10) \times 10^{-9} \left( \frac{x_f}{0.3} \right)^2.
\]

(14)

\(^3\)For simplicity we have neglected the effect of heating of the photons via \( e^+ e^- \) annihilations. Note that the same effect occurs for the mirror photons which are heated by the annihilations of \( e'^{+} e'^{-} \), so that \( x_f \) is approximately unchanged by this effect.
Successful large scale structure studies[7, 8] suggest a rough bound on \( x_f \) of \( x_f \gtrsim 0.3 \). Our result, Eq.(14), then suggests a rough bound on \( \epsilon \) of \( \epsilon \lesssim 10^{-9} \).

In conclusion, previous work has shown that the mirror dark matter candidate can explain the DAMA/Libra annual modulation signal consistently with the null results of the other direct detection experiments provided that there exists photon-mirror photon kinetic mixing of strength \( \epsilon \sim 10^{-9} \). Here we have examined the implications of this kinetic mixing for early Universe cosmology, where we showed that it is consistent with constraints from ordinary BBN and CMB/LSS data.

Appendix

Here we shall examine the quantity \( \langle \sigma v_{\text{Msd}} \rangle \) and derive Eq.(6) and Eq.(11) used in our analysis. Following ref.[27], we have:

\[
\langle \sigma v_{\text{Msd}} \rangle = \frac{\int \sigma v_{\text{Msd}}(E_1 + E_2) e^{-E_1/T} e^{-E_2/T} d^3p_1 d^3p_2}{\int e^{-E_1/T} e^{-E_2/T} d^3p_1 d^3p_2} \tag{15}
\]
where \( p_1 \) and \( p_2 \) are the three-momenta and \( E_1 \) and \( E_2 \) the energies of the colliding particles in the cosmic comoving frame. Recall that \( \mathcal{E} = E_1 + E_2 \) is the energy transfer per collision. As elaborated in ref.[27], evaluation of these integrals can be facilitated by changing variables to \( \mathcal{E}_\pm = E_1 \pm E_2 \) and \( s = 2m_e^2 + 2E_1E_2 - 2p_1p_2 \cos \theta \). In terms of these variables the volume element becomes

\[
d^3p_1d^3p_2 = 2\pi^2 E_1E_2dE_+dE_-ds
\]

and

\[
\sigma v_{\text{coll}} e^{-E_1/T} e^{-E_2/T} d^3p_1d^3p_2 = 2\pi^2 \int dE_+E_+ \int dE_- \int ds \sigma v_{\text{coll}} E_1 E_2 e^{-E_+/T}
\]

with integration region \( |E_-| \leq \sqrt{1 - \frac{4m_e^2}{s} \sqrt{E_+^2 - s}}, \ E_+ \geq \sqrt{s}, \ s \geq 4m_e^2 \). Performing the \( E_- \) integration, we have:

\[
\int \sigma v_{\text{coll}} e^{-E_1/T} e^{-E_2/T} d^3p_1d^3p_2 = 4\pi^2 \int ds F \sqrt{1 - \frac{4m_e^2}{s}} \int dE_+ e^{-E_+/T} \sqrt{E_+^2 - s} E_+
\]

where \( \sigma F = \sigma v_{\text{coll}} E_1 E_2 \) and \( F = \frac{1}{2}\sqrt{s(s - 4m_e^2)} \). Also, as discussed in ref.[27]

\[
\int e^{-E_1/T} e^{-E_2/T} d^3p_1d^3p_2 = \left[ 4\pi m_e^2 T K_2(m_e/T) \right]^2
\]

where \( K_2 \) is the modified Bessel function of order 2. Hence we see that

\[
\langle \sigma v_{\text{coll}} \mathcal{E} \rangle = \frac{1}{8m_e^4T^2 K_2^2(m_e/T)} \int_{4m_e^2}^{\infty} ds \mathcal{E} (s - 4m_e^2) \sqrt{s} \int_{\sqrt{s}}^{\infty} dE_+ e^{-E_+/T} \sqrt{E_+^2 - s} - 1.
\]

In the \( m_e \to 0 \) limit, where \( \sigma = \frac{4\pi \alpha^2 \sqrt{s}}{3s} \), and using the dimensionless variable \( z \equiv E_+/\sqrt{s} \), we find:

\[
\int \sigma v_{\text{coll}} e^{-E_1/T} e^{-E_2/T} d^3p_1d^3p_2 = \frac{8\pi^3 \alpha^2 \epsilon^2}{3} \int_0^1 ds s^{3/2} \int_1^{\infty} dz e^{-z\sqrt{s}/T} z \sqrt{z^2 - 1}
\]

\[
= 128\alpha^2 \epsilon^2 \pi^3 T^5 I
\]

where

\[
I \equiv \int_1^{\infty} \frac{\sqrt{z^2 - 1}}{z^4} \ dz = \frac{1}{3}.
\]

Also,

\[
\int e^{-E_1/T} e^{-E_2/T} d^3p_1d^3p_2 = \left[ 4\pi m_e^2 TK_2(m_e/T) \right]^2
\]

\[
= 64\pi^2 T^6 \ \text{in the} \ m_e \to 0 \ \text{limit}.
\]
Thus we find:

$$\langle \sigma v_{\text{Mol}} \rangle = \frac{2\pi \alpha^2 \epsilon^2}{3T}. \quad (24)$$

Our results for $\langle \sigma v_{\text{Mol}} \rangle$, Eq.(20) [or Eq.(24) for the $m_e \to 0$ limit], have assumed Maxwellian distributions for the fermions to simplify the integrals. In the $m_e \to 0$ limit, it is possible to evaluate the integrals for the realistic case of Fermi-Dirac distributions. In which case, one finds:

$$\langle \sigma v_{\text{Mol}} \rangle = \frac{4\pi \alpha^2 \epsilon^2}{3T} \frac{I_1}{I_2} \quad (25)$$

where

$$I_1 = \int_0^\infty dz \int_0^\infty dx \int_0^{\sqrt{x^2-z}} dy \frac{x}{1 + e^{x+y}} \frac{1}{1 + e^{x-y}}$$

$$I_2 = \int_0^\infty dz \int_0^\infty dx \int_0^{\sqrt{x^2-z}} dy \frac{x^2 - y^2}{1 + e^{x+y}} \frac{1}{1 + e^{x-y}} \quad (26)$$

We find numerically that:

$$I_1 \simeq 0.39, \; I_2 \simeq 0.84 \Rightarrow \frac{I_1}{I_2} \simeq 0.46. \quad (27)$$

Thus, we see that the approximation of using Maxwellian statistics overestimates $\langle \sigma v_{\text{Mol}} \rangle$ by around 8%.

Acknowledgements

The work of R.F. was supported by the Australian Research Council. P.C. acknowledges support from the Belgian fund for scientific research (FNRS).

References

[1] R. Foot, H. Lew and R. R. Volkas, Phys. Lett. B272, 67 (1991). The idea of a mirror sector was 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). The idea that the mirror particles might be the dark matter was first discussed in: S. I. Blinnikov and M. Yu. Khlopov, Sov. J. Nucl. Phys. 36, 472 (1982); Sov. Astron. 27, 371 (1983).

[2] H. Hodges, Phys. Rev. D47, 456 (1993).

[3] R. Foot and R. R. Volkas, Astropart. Phys. 7, 283 (1997) [arXiv: hep-ph/9612245]; Phys. Rev. D61, 043507 (2000) [arXiv: hep-ph/9904336].

[4] Z. Silagadze, Phys. Atom. Nucl. 60, 272 (1997) [arXiv: hep-ph/9503481]; S. Blinnikov, arXiv: astro-ph/9801015; R. Foot, Phys. Lett. B452, 83 (1999) [arXiv: astro-ph/9902065].
[5] N. F. Bell and R. R. Volkas, Phys. Rev. D59, 107301 (1999) [arXiv: astro-ph/9812301].

[6] Z. Berezhiani, D. Comelli and F. L. Villante, Phys. Lett. B503, 362 (2001) [arXiv: hep-ph/0008105].

[7] A. Yu. Ignatiev and R. R. Volkas, Phys. Rev. D68, 023518 (2003) [arXiv: hep-ph/0304260].

[8] Z. Berezhiani, P. Ciarcelluti, D. Comelli and F. L. Villante, Int. J. Mod. Phys. D14, 107 (2005) [arXiv: astro-ph/0312605]; P. Ciarcelluti, PhD thesis, 2003 [arXiv: astro-ph/0312607]; Frascati Phys. Ser. 555, 1 (2004) [arXiv: astro-ph/0409629]; Int. J. Mod. Phys. D14, 187 (2005) [arXiv: astro-ph/0409630]; Int. J. Mod. Phys. D14, 223 (2005) [arXiv: astro-ph/0409633].

[9] P. Ciarcelluti, arXiv: 0809.0668 (2008); P. Ciarcelluti and A. Lepidi, arXiv: 0809.0677 (2008).

[10] L. Bento and Z. Berezhiani, Phys. Rev. Lett. 87, 231304 (2001) [arXiv: hep-ph/0107281]; arXiv: hep-ph/0111116.

[11] R. Foot and R. R. Volkas, Phys. Rev. D68, 021304 (2003) [arXiv: hep-ph/0304261]; Phys. Rev. D69, 123510 (2004) [arXiv: hep-ph/0402267].

[12] R. Foot and R. R. Volkas, Phys. Rev. D70, 123508 (2004) [arXiv: astro-ph/0407522].

[13] Z. Berezhiani, S. Cassisi, P. Ciarcelluti, and A. Pietrinferni, Astropart. Phys. 24, 495 (2006) [arXiv: astro-ph/0507153]; F. Sandin and P. Ciarcelluti, arXiv: 0809.2942 (2008).

[14] R. Foot and S. Mitra, Astropart. Phys. 19, 739 (2003) [arXiv: astro-ph/0211067]; Phys. Lett. B558, 9 (2003) [arXiv: hep-ph/0303005]; Phys. Lett. A315, 178 (2003) [arXiv: cond-mat/0306561].

[15] R. Foot and Z. K. Silagadze, Int. J. Mod. Phys. D14, 143 (2005) [arXiv: astro-ph/0404515].

[16] Z. K. Silagadze, arXiv: 0808.2595 (2008).

[17] R. Foot, Int. J. Mod. Phys. D13, 2161 (2004) [arXiv: astro-ph/0407623].

[18] J. L. Feng, H. Tu and H-B. Yu, arXiv: 0808.2318 (2008).

[19] R. Foot, Phys. Rev. D78, 043529 (2008) [arXiv: 0804.4518].

[20] R. Foot, Phys. Rev. D69, 036001 (2004) [arXiv: hep-ph/0308254]; R. Foot, Mod. Phys. Lett. A19, 1841 (2004) [arXiv: astro-ph/0405362]; R. Foot, Phys. Rev. D74, 023514 (2006) [arXiv: astro-ph/0510705].
[21] R. Bernabei et al. (DAMA Collaboration), arXiv: 0804.2741 (2008).
[22] R. Foot and X-G. He, Phys. Lett. B267, 509 (1991).
[23] B. Holdom, Phys. Lett. B166, 196 (1986).
[24] R. Foot, Int. J. Mod. Phys. A19, 3807 (2004) [arXiv: astro-ph/0309330].
[25] E. W. Kolb, D. Seckel and M. S. Turner, Nature 314, 415 (1985); H. Hodges, Phys. Rev. D47, 456 (1993); Z. G. Berezhiani, A. D. Dolgov and R. N. Mohapatra, Phys. Lett. B375, 26 (1996) [arXiv: hep-ph/9511221].
[26] E. D. Carlson and S. L. Glashow, Phys. Lett. B193, 168 (1987).
[27] P. Gondolo and G. Gelmini, Nucl. Phys. B360, 145 (1991).