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

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ABSTRACT

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. It follows that the masses of the mirror particles are fixed to be the same as their ordinary counterparts. 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 [2–16]. 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 $U(1)_{\rm em}$ [23]):

$$\mathcal{L}_{\rm mix} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} \qquad (1)$$

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 $\epsilon q e$, 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]. It will be tested further by on-going direct detection experiments, and potentially laboratory experiments involving orthopositronium studies [25,26].

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 mir-

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ror radiation sectors in the early Universe due to some physics at early times (for specific models, see e.g. [27]). 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 $T'/T \lesssim 0.3$. However, if photon–mirror photon kinetic mixing exists, it can potentially thermally populate the mirror sector. For example, Carlson and Glashow [28] 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 ϵ, 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 $e^+e^- \to e'^+e'^-$. This leads to the generation of energy density in the mirror sector of:

$$\frac{\partial \rho'}{\partial t} = n_{e^+} n_{e^-} \langle \sigma v_{\mathrm{Møl}} \mathcal{E} \rangle, \tag{2}$$

where $\mathcal{E}$ is the energy transferred in the process, $v_{møl}$ is the Møller velocity (see e.g. Ref. [29]), and $n_{e^-} \simeq n_{e^+} \simeq \frac{3\zeta(3)}{2\pi^2} T^3$.

It is useful to consider the quantity: ρ'/ρ, in order to cancel the time dependence due to the expansion of the Universe [recall $\rho = \pi^2 g T^4/30$]. Using the time temperature relation:

$$t = 0.3 g^{-1/2} \frac{M_{\mathrm{Pl}}}{T^2} \tag{3}$$

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

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

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

$$\langle \sigma v_{\mathrm{Møl}} \mathcal{E} \rangle = \frac{\int \sigma v_{\mathrm{Møl}} (E_1 + E_2) \frac{1}{1+e^{E_1/T}} \frac{1}{1+e^{E_2/T}} d^3p_1 \, d^3p_2}{\int \frac{1}{1+e^{E_1/T}} \frac{1}{1+e^{E_2/T}} d^3p_1 \, d^3p_2}, \tag{5}$$

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 A) that in the massless electron limit:

$$\langle \sigma v_{\mathrm{Møl}} \mathcal{E} \rangle = \frac{2\pi \alpha^2 \epsilon^2}{3T}, \tag{6}$$

and Eq. (4) reduces to:

$$\frac{d(\rho'/\rho)}{dT} = \frac{-A}{T^2}, \tag{7}$$

where

$$A = \frac{27\zeta(3)^2 \alpha^2 \epsilon^2 M_{\mathrm{Pl}}}{\pi^5 g \sqrt{g}}. \tag{8}$$

Note that the $e'^{\pm}$ will thermalize with γ'. 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 $G_F^2 T'^5 \ll \frac{\sqrt{g} T^2}{0.3 M_{\mathrm{Pl}}}$]. 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 $g'/g \approx 22/43$.

Eq. (7) has the analytic solution:

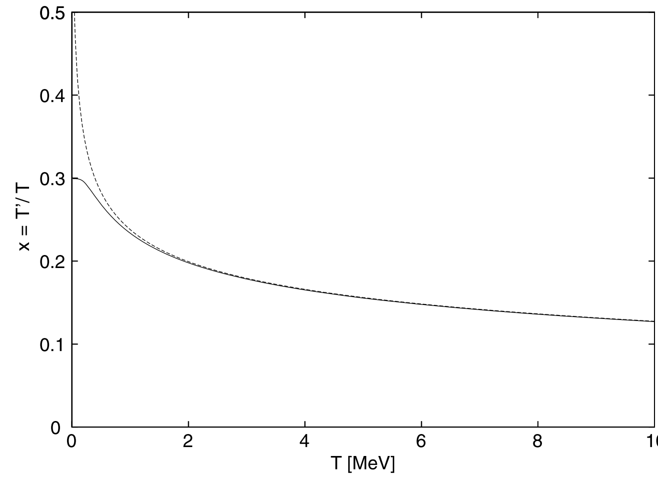

Fig. 1. Evolution of $x = T'/T$ for $\epsilon = 8.5 \times 10^{-10}$. The solid line is the numerical solution including the effects of the electron mass, while the dashed line is the analytic result [using Eq. (9)], which holds in the massless electron limit. As expected the two solutions agree in the $T \gtrsim 1$ MeV region, where the effects of the electron mass should be negligible.

$$\frac{T'}{T} = \left(\frac{g}{g'} A \right)^{1/4} \left[\frac{1}{T} - \frac{1}{T_i} \right]^{1/4}, \tag{9}$$

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:

$$n_{e^-} = \frac{1}{\pi^2} \int_{m_e}^{\infty} \frac{\sqrt{E^2 - m_e^2}\, E}{1 + \exp(E/T)} dE \tag{10}$$

and, as we discuss in Appendix A,

$$\langle \sigma v_{\mathrm{Møl}} \mathcal{E} \rangle = \frac{1}{8 m_e^4 T^2 K_2^2(m_e/T)} \int_{4m_e^2}^{\infty} ds\, \sigma \left(s - 4m_e^2\right) \sqrt{s} \times \int_{\sqrt{s}}^{\infty} dE_+ \, e^{-E_+/T} E_+ \sqrt{\frac{E_+^2}{s} - 1} \tag{11}$$

where the cross section is:

$$\sigma = \frac{4\pi}{3} \alpha^2 \epsilon^2 \frac{1}{s^3} \left(s + 2m_e^2\right)^2. \tag{12}$$

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[1]

$$\epsilon \simeq 8.5 \times 10^{-10} \left(\frac{x_f}{0.3} \right)^2 \tag{13}$$

where x_f is the final value ($T \to 0$) of $x = T'/T$. In Fig. 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:

[1] 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.

(a) Using Maxwellian statistics instead of Fermi–Dirac statistics to simplify the estimate of $\langle \sigma v_{\text{Møl}} \mathcal{E} \rangle$. Using Fermi–Dirac statistics should decrease the interaction rate by around 8% as discussed in Appendix A. (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:

$$\epsilon = (1.0 \pm 0.10) \times 10^{-9} \left(\frac{x_f}{0.3} \right)^2. \tag{14}$$

Successful large scale structure studies [7,8] suggest a rough bound on x_f of $x_f \lesssim 0.3$. Our result, Eq. (14), then suggests the rough bound[2] $\epsilon \lesssim 10^{-9}$.

Our estimate for the production of mirror $e^{\pm}$ in the early Universe is broadly similar to the numerical estimate given in [30,31] for milli-charged particles. Note however, one cannot translate the results of Ref. [30] into an evolution equation for T'/T or even a bound on epsilon for the mirror model, since the mirror model has a specific set of particles in thermal equilibrium with temperature T', which is not equivalent to the production of a single milli-charged particle species. Furthermore, the analytic equation derived in Ref. [30] is for the interaction rate $n_e \langle \sigma v_{\text{Møl}} \rangle$, however, the equation one needs is for the mean energy transfer $n_e \langle \sigma v_{\text{Møl}} \mathcal{E} \rangle$, which we have derived in Eq. (6).

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.

Note added

After completion of the first draft of this Letter, the article [32] appeared. In that work, they obtained a different conclusion to our result. Unfortunately, since their work was largely numerical, we couldn't ascertain the reason for the difference.

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Appendix A

Here we shall examine the quantity $\langle \sigma v_{\text{Møl}} \mathcal{E} \rangle$ and derive Eq. (6) and Eq. (11) used in our analysis. Following Ref. [29], we have:

$$\langle \sigma v_{\text{Møl}} \mathcal{E} \rangle = \frac{\int \sigma v_{\text{Møl}} (E_1 + E_2) e^{-E_1/T} e^{-E_2/T} \, d^3p_1 \, d^3p_2}{\int e^{-E_1/T} e^{-E_2/T} \, d^3p_1 \, d^3p_2} \tag{15}$$

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. [29], evaluation of these integrals can be facilitated by changing variables to $E_{\pm} \equiv E_1 \pm E_2$ and $s = 2m_e^2 + 2E_1E_2 - 2p_1p_2\cos\theta$. In terms of these variables the volume element becomes

$$d^3p_1 \, d^3p_2 = 2\pi^2 E_1 E_2 \, dE_+ \, dE_- \, ds \tag{16}$$

and

$$\int \sigma v_{\text{Møl}} \mathcal{E} e^{-E_1/T} e^{-E_2/T} \, d^3p_1 \, d^3p_2 = 2\pi^2 \int dE_+ \, E_+ \int dE_- \int ds \, \sigma v_{\text{Møl}} E_1 E_2 e^{-E_+/T} \tag{17}$$

with integration region $|E_-| \leqslant \sqrt{1 - \frac{4m_e^2}{s}} \sqrt{E_+^2 - s}$, $E_+ \geqslant \sqrt{s}$, $s \geqslant 4m_e^2$. Performing the E_- integration, we have:

$$\int \sigma v_{\text{Møl}} \mathcal{E} e^{-E_1/T} e^{-E_2/T} \, d^3p_1 \, d^3p_2 = 4\pi^2 \int ds \, \sigma F \sqrt{1 - \frac{4m_e^2}{s}} \int dE_+ \, e^{-E_+/T} \sqrt{E_+^2 - s} \, E_+ \tag{18}$$

where $\sigma F = \sigma v_{\text{Møl}} E_1 E_2$ and $F = \frac{1}{2}\sqrt{s(s - 4m_e^2)}$. Also, as discussed in Ref. [29]

$$\int e^{-E_1/T} e^{-E_2/T} \, d^3p_1 \, d^3p_2 = \left[4\pi m_e^2 T K_2(m_e/T) \right]^2 \tag{19}$$

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

$$\langle \sigma v_{\text{Møl}} \mathcal{E} \rangle = \frac{1}{8m_e^4 T^2 K_2^2(m_e/T)} \int_{4m_e^2}^{\infty} ds \, \sigma \left(s - 4m_e^2 \right) \sqrt{s} \times \int_{\sqrt{s}}^{\infty} dE_+ \, e^{-E_+/T} E_+ \sqrt{\frac{E_+^2}{s} - 1}. \tag{20}$$

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

$$\int \sigma v_{\text{Møl}} \mathcal{E} e^{-E_1/T} e^{-E_2/T} \, d^3p_1 \, d^3p_2 = \frac{8\pi^3\alpha^2\epsilon^2}{3} \int_0^{\infty} ds \, s^{3/2} \int_1^{\infty} dz \, e^{-z\sqrt{s}/T} z \sqrt{z^2 - 1} = 128\,\alpha^2\epsilon^2\pi^3 T^5 I, \tag{21}$$

where

$$I \equiv \int_1^{\infty} \frac{\sqrt{z^2 - 1}}{z^4} \, dz = \frac{1}{3}. \tag{22}$$

Also,

$$\int e^{-E_1/T} e^{-E_2/T} \, d^3p_1 \, d^3p_2 = \left[4\pi m_e^2 T K_2(m_e/T) \right]^2 = 64\pi^2 T^6 \quad \text{in the } m_e \to 0 \text{ limit}. \tag{23}$$

Thus we find:

$$\langle \sigma v_{\text{Møl}} \mathcal{E} \rangle = \frac{2\pi\alpha^2\epsilon^2}{3T}. \tag{24}$$

[2] Note that for $\epsilon \sim 10^{-9}$ supernovae will emit around half their energy into mirror particles and thus one can suspect this as a rough supernova limit [31]. This limit is consistent with our bound from early Universe cosmology.

Our results for $\langle \sigma v_{\text{Møl}} \mathcal{E} \rangle$, 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:

$$\langle \sigma v_{\text{Møl}} \mathcal{E} \rangle = \frac{4\pi \alpha^2 \epsilon^2}{3T} \frac{I_1}{I_2}, \tag{25}$$

where

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

$$I_2 = \int_0^\infty dz \int_{\sqrt{z}}^\infty dx \int_0^{\sqrt{x^2-z}} dy \, \frac{x^2-y^2}{1+e^{x+y}} \frac{1}{1+e^{x-y}}. \tag{26}$$

We find numerically that:

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

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

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