Cosmological bounds on the ”millicharges” of mirror particles

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Abstract

Mirror world, a parallel hidden sector with microphysics identical to ordinary particle physics, can have several interesting phenomenological and astrophysical implications and mirror matter can be a natural candidate for dark matter in the universe. If the ordinary and the mirror photons have a kinetic mixing due to the Lagrangian term \((\epsilon/2)F_{\mu\nu}F'_{\mu\nu}\), then mirror particles effectively acquire the electric charges \(\sim \epsilon\) with respect to the ordinary photon, so that they become a sort of particles historically coined as ”millicharged” though nowadays they must be called more appropriately as ”nanocharged”. In this paper we revise the cosmological bounds on the kinetic mixing parameter and in the case of exact mirror parity set an upper limit \(\epsilon < 3 \times 10^{-10}\). Much weaker limit can be obtained in the case of asymmetric mirror sector, with an electroweak symmetry breaking scale larger than the ordinary electroweak scale.

1 Introduction

The old idea that there can exist a hidden mirror sector of particles and interactions which is an exact duplicate of our visible world \([1]\) has attracted a significant interest over the last years. The mirror theory is based on the product of two identical gauge factors \(G \times G'\) with an identical particle content.

The general procedure of doubling the gauge factors can be applied to any gauge group, such as the standard model one \([SU(3) \times SU(2) \times U(1)] \times [SU(3)' \times SU(2)' \times U(1)']\) or the grand unified theories such as \(SU(5) \times SU(5)'\), etc. (In the following, to distinguish between quantities referred to the ordinary and to the mirror sector, the latter ones are marked with prime '). Also, a ”double” gauge factor naturally emerges in the context of \(E_8 \times E_8'\) superstring.

If the mirror world exists, universe should contain, along with the ordinary particles: electrons, nucleons, photon, etc. also their mirror partners: mirror electrons, mirror nucleons, mirror photon, etc., with exactly the same mass spectrum and interaction properties (mirror parity). Any neutral ordinary particle, elementary or composite, can have a mixing with its mirror counterpart exactly degenerate in mass. E.g., photon can have kinetic mixing with M-photon \([2,3,4]\), ordinary (active) neutrinos can mix with mirror (sterile) neutrinos with interesting astrophysical implications \([5,6]\), neutral \(\pi\) mesons can mix with mirror \(\pi'\) mesons, neutrons with mirror neutrons.
Such mixings can be induced by the effective interactions between the O- and M-fields mediated by some messengers, which may be some heavy gauge singlet particles, or heavy gauge bosons interacting with both sectors [10].

Mirror matter, being invisible in terms of ordinary photon and interacting with ordinary matter only gravity, is a natural candidate for dark matter (DM) consistent with cosmological tests [11, 13, 14]. In addition, the baryon asymmetry of the Universe can be generated via out-of-equilibrium $B - L$ and $CP$ violating processes between the visible and dark matter fractions in the universe [15]. Such a mechanism can explain the closeness between the baryonic and dark matter fractions in the universe, providing naturally $\Omega_{B}^{\prime}/\Omega_{B} \sim 1 \div 5$ as far as the ordinary and mirror baryons have exactly the same masses [16, 17].

Cosmological aspects, and in particular, Big Bang Nucleosynthesis (BBN) bounds, require that the temperature of mirror sector $T^{\prime}$ should be smaller then the temperature $T$ of ordinary sector. BBN is sensitive to the energy density of the universe at $T \sim 1$ MeV [18], which is usually parametrized in terms of the effective degrees of freedom $g^{* T} = g_{st}^{* T} + \Delta g^{* T}$ or the effective number of extra-neutrinos $\Delta N_{\nu} = \Delta g^{* T}/1.75$, where $\Delta g^{* T}$ measures the contribution of any extra particle species in addition to standard input $g_{st}^{* T} = 10.75$ as contributed by photons $\gamma$, electron-positrons $e, \bar{e}$ and three neutrino species $\nu_{e, \mu, \tau}$ at $T \sim 1$ MeV. Therefore, the contribution of mirror photons $\gamma^{\prime}$, mirror electron-positrons $e^{\prime}, \bar{e}^{\prime}$ and mirror neutrinos $\nu^{\prime}_{e, \mu, \tau}$ would correspond to

$$\left( \frac{\rho^{\prime}}{\rho} \right)_{BBN} = 0.16 \Delta N_{\nu} = x^{4}, \tag{1}$$

or $\Delta N_{\nu} \simeq 6.14 x^{4}$, where $x = T^{\prime}/T$ is a temperature ratio between two sectors [11]. Hence, a conservative bound on the number of extra-neutrinos $\Delta N_{\nu} < 0.5$ implies $(\rho^{\prime}/\rho)_{BBN} < 0.08$, or $x < 0.5$. A detailed analysis of the temporal evolution of the number of degrees of freedom in both sectors can be found in [12].

The cosmological constraints from the CMB and large scale structure of the Universe lead to more stringent limits, if one assumes that dark matter is entirely made of mirror baryons. In this case, the perturbations in the mirror baryon fluid cannot grow before the mirror photon decoupling which occurs at the redshift $z^{\prime}_{dec} \simeq x^{-1} z_{dec}$ [11], where $z_{dec} \approx 1100$ is the redshift or the ordinary photon decoupling from the matter. However, for $x < 0.3$ the mirror photons decouple before the matter radiation epoch $z_{eq} \approx 3000$ and so the density perturbations at the scales larger than the corresponding horizon size can undergo the linear growth. In this case, as it was shown in [14] via explicit computations, the linear power spectrum characterizing the large scale structures (LSS), at the scales $k/h < 0.2$/Mpc or so, as well as the power spectrum of the CMB oscillations, are practically indistinguishable from the standard CDM predictions. Somewhat stronger bounds emerge from the galaxy formation constraint. For example, by requiring that the density perturbations corresponding to the galaxies like a Milky Way are not Silk-damped, we would get a bound $x < 0.2$.

3 In principle, ordinary and mirror sectors can have also different gravities. The ordinary to mirror graviton mixing and its cosmological implications were discussed in Ref. [8].

4 There is also a possibility that mirror parity is spontaneously broken, and the electroweak symmetry breaking scale in mirror sector is larger than the ordinary electroweak scale [3, 9]. In this case mirror world would become a particular type of a shadow world, with more heavy but less collisional and dissipative matter more resembling the cold dark matter (CDM), that we discuss in Section 3.
while the “bottom-up” formation of smaller structures as dwarf galaxies as well as constraints from the Lyman-α forest would require $x < 0.1$ or so [11, 13, 14]. Nevertheless, in the following we take a more conservative limit $x < 0.3$ which is in fact a robust bound even in the case when mirror baryons constitute only a fraction of dark matter while the rest is provided by some kind of the CDM [14], e.g. if $\Omega_B' = \Omega_B$ as in the limiting case implied by the unified baryogenesis mechanism between the ordinary and mirror sectors [15].

The difference of the temperatures $T$ and $T'$ during the cosmological evolution can occur if after inflation ordinary and mirror sectors are heated at different temperatures; then they evolve adiabatically with the Universe expansion, without strong first order phase transitions, so that in both sectors the entropies are separately conserved. Therefore, as far as there is no substantial energy exchange between ordinary and mirror sectors, the ratio $x = T'/T \simeq (s'/s)^{1/3}$ remains nearly constant in time. Obviously, this is correct if during and after the inflation there is no significant entropy exchange between the ordinary and mirror sectors, which would be the case if they interact only via gravity. However, if there are other particle processes between two sectors, they should be weak enough in order not to bring two sectors into thermal equilibrium with each other.

One of the most interesting phenomena which may reveal the mirror sector is the ordinary photon-mirror photon kinetic mixing, which arises when the term $(\epsilon/2)F_{\mu\nu}F'_{\mu\nu}$ is inserted in the Lagrangian [2, 3, 4]. This term is allowed by symmetries as far as the field strength tensors of $U(1)$ gauge bosons $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$, etc., are gauge invariants. Then the complete electromagnetic Lagrangian reads

$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu} + 2\epsilon F_{\mu\nu}F'^{\mu\nu}) - e q_f A_\mu(\bar{f}\gamma^\mu f) - e' q_f A'_{\mu}(\bar{f}'\gamma^\mu f') - \epsilon e q_f A_\mu(\bar{f}'\gamma^\mu f'),$$

where $f$ and $f'$ stand for the charged particles as electrons or protons respectively of ordinary and mirror sectors. Performing the unitary transformation and the rescaling of the fields, the kinetic terms can be diagonalized and canonically normalized [2, 19]. One can choose a basis in which ordinary charged particles $f$ interact only with one combination $A_\mu$ (“normal” photon), and the other combination $A'_{\mu}$ of $A_\mu$ and $A'_{\mu}$; a sort of paraphoton, interacts only with $f'$ while $f$s are ”sterile” with respect to it. Therefore, in this basis the interaction term in the Lagrangian (2) becomes:

$$\mathcal{L}_{int} = -e q_f A_\mu(\bar{f}\gamma^\mu f) - e' q_f A'_{\mu}(\bar{f}'\gamma^\mu f') - \epsilon e q_f A_\mu(\bar{f}'\gamma^\mu f'),$$

so that charged mirror particles $f'$ electromagnetically interact also with the normal photon, with the interaction constant being suppressed by the kinetic mixing parameter $\epsilon$. In other words, a mirror particle with mirror electric charge $q_f$ acquires also tiny ordinary electric charges $\epsilon q_f$. For historical reasons such particles were called millicharged particles (or MCPs). From the point of view of the present cosmological limits on $\epsilon$ are about $10^{-9}$, it would be more proper to name them as possible nanocharged particles (NCPs).

The photon-mirror photon kinetic mixing can induce ordinary-mirror positronium oscillations and in principle can be detected via observing the invisible decay channels of orto-positronium [3, 20]. The present experimental limits on the positronium decay imply $\epsilon \leq 3 \times 10^{-7}$. However sensibility of experiments can be improved to the level $\epsilon \sim$ few $\times 10^{-9}$ [21].
On the other hand, the nanocharged mirror nuclei, if they constitute dark matter, could be detected by dark matter detectors. In particular the results of DAMA/NaI experiment for dark matter detection could be nicely explained by the scattering of nanocharged mirror nuclei if $\epsilon \sim 10^{-9}$.

A few months ago the first results from the DAMA/Libra experiment and the combined analysis with DAMA/NaI have been published. Both experiments performed a model-independent and low-threshold dark matter (DM) search; the recorded annual modulation signal has phase and periodicity compatible with the dark matter expected signature.

Soon after, an interpretation of the DAMA results in terms of mirror matter was proposed and compatibility with other experiments, such as CDMS and XENON10, was analyzed. This interpretation is based on the idea that the signal detected in DAMA may be due to scattering of nanocharged mirror nuclei on ordinary matter. In particular, the best candidate for reproducing the DAMA data and being unobservable in other experiments is the nanocharged mirror oxygen. The analysis performed in shows that the interaction rate is proportional to $(Z^A_A')^2 \xi_{A'}$ where $\xi_{A'}$ is the halo mass fraction of the species $A'$, in our case mirror oxygen, that is $\xi_{A'} = n_{A'} M_{A'}/(0.3 \text{GeV/cm}^3)$. In particular, the DAMA data can be reproduced if $\epsilon \sqrt{\xi_{O'}} \sim 3 \times 10^{-10}$, where $\xi_{O'}$ is the mirror oxygen mass fraction which is typically assumed to vary between $10^{-3}$ and $10^{-1}$, that implies $\epsilon \sim 10^{-8} \div 10^{-9}$.

However, if the mirror particles are nanocharged, there are electromagnetic processes like $e\bar{e} \leftrightarrow e'\bar{e}'$ leading to energy transfer between the two sectors, with the efficiency $\propto \epsilon^2$. Hence the mirror sector is heated and the temperature ratio $x = T'/T$ increases. In this way, the value of the kinetic mixing parameter $\epsilon$ can be restricted by the cosmological bounds on $x$.

The BBN constraints on the photon-mirror photon kinetic mixing were discussed at first by Carlson and Glashow in 1987 and the bound $\epsilon < 3 \times 10^{-8}$ was reported. This limit however needs to be updated in the light of the modern data on the primordial element abundances.

In this paper we revisit the cosmological bounds on $\epsilon$ or, in other words, bounds on the nanocharges of mirror particles, that can be imposed by the analysis of the BBN and the CMB epochs. Hence arises an important difference between the bound on $x$ coming from BBN and the one from CMB: the first applies at $T_{BBN} \sim 1 \text{ MeV}$, while the second applies at the matter radiation equality epoch, when $T_{CMB} \sim 1 \text{ eV}$. This difference must be taken into account when calculating bounds on the model parameters, that is, the contributions to the mirror energy must be calculated up to $T_{CMB}$ when applying the CMB limit on $x$. We also study the case of spontaneously broken mirror parity, in which case mirror particles, and in particular, mirror electron becomes heavier than the ordinary ones, which significantly relaxes the stringent bounds on the photon-mirror photon kinetic mixing obtained for the case of exact mirror parity.

5 The generic NCPs, without a specific reference to the mirror model, have been worked out in Ref. [26], where the bounds from accelerator experiments, BBN, globular clusters, supernova 1987A, white dwarfs and CMB were studied. However, more attention was devoted to the light NCPs, lighter than the electron, for which the astrophysical bounds are more stringent.
2 Bounds on the kinetic mixing parameter

If the kinetic mixing between the photons is present, there are electromagnetic processes involving ordinary and mirror particles and leading to energy and entropy exchanges between the two sectors. At first order in the coupling constant $e$ there can be pair annihilation and production $e \bar{e} \leftrightarrow e' \bar{e}'$, elastic scatterings like $ee \leftrightarrow ee'$ and the plasmon decay $\gamma \rightarrow e' \bar{e}'$. For our purposes, only the first process is significant. Indeed scattering processes, which can take place only after mirror particles have been created, lead to an energy transfer between the two sectors lower than that from the pair annihilation at least by a factor $\sim x^3$. Plasmon effects, which generally give a dominant contribution for the light MCP, with $m \ll m_e$ are ineffective for $m \geq m_e$ and therefore negligible for us.

The amplitude of the annihilation process $e \bar{e} \rightarrow e' \bar{e}'$, for $m_e = m_{e'} = m$, is $\epsilon$ times the $s$-channel amplitude for the process $e \bar{e} \rightarrow e \bar{e}$. The corresponding cross section reads

$$\sigma_\epsilon = \epsilon^2 \frac{4 \pi \alpha^2}{3} \frac{(s + 2m^2)^2}{s^3}, \quad (4)$$

To calculate the energy exchanges between the two sectors we need the interaction rate $\Gamma_\epsilon$, which is defined in terms of the average the cross section times the velocity of colliding particles, $\Gamma_\epsilon \equiv \langle \sigma_\epsilon v \rangle n$. For relativistic electrons, $T > m$, $\Gamma$ has the form

$$\Gamma_\epsilon = \epsilon^2 \Gamma_1, \quad \Gamma_1 = 0.2 \alpha^2 T \quad (5)$$

which should be compared with the Hubble parameter

$$H = 1.66 \ g_{sT}^{1/2} \frac{T^2}{M_P}, \quad (6)$$

$M_P$ being the Planck mass and $g_{sT}$ the total number of degrees of freedom at the temperature $T$. At the BBN epoch, $T = 0.8$ MeV, we have $g_{sT} \simeq 10$ and hence we see that $\Gamma_\epsilon < H$ is satisfied if $\epsilon < 5 \times 10^{-9}$ or so [27].

However, this is only an estimate and for deriving more precise bounds on $\epsilon$ more accurate calculations are needed, by solving corresponding Boltzmann equations and taking into account the low energy tale (below 1 MeV) of the cross section of the processes $e \bar{e} \rightarrow e' \bar{e}'$. The latter should be treated more precisely for setting the BBN bounds on $\epsilon$, and more importantly, for discussing the process at the lower temperatures, $T \ll 1$ MeV, since the corresponding asymptotic value of $T'/T$ is relevant for the cosmological features of the mirror dark matter related to the mirror photon decoupling and the growth of primordial perturbations. When $T < 1$ MeV the relativistic approximation is no longer valid, so we cannot use $\Gamma$ in eq. [25]. The thermal average at low temperature, when $T \leq 3m_e$, can be calculated and it has the form [28]:

$$\langle \sigma_\epsilon v \rangle = \frac{1}{8m_e^4 T K_1^2(m_e/T)} \int_{4m_e^2}^{\infty} \sigma_\epsilon \cdot (s - 4m_e^2) \sqrt{s} K_1 \left( \frac{\sqrt{s}}{T} \right) ds \quad (7)$$

The plasmon decay becomes effective at $T \geq 10$ MeV since the plasmon energy $\omega_P \sim 0.1T$ must be at least $\sim 2m_e$. 

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where $K_1$ and $K_2$ are the modified Bessel functions of the second kind, and $v$ is the M"oller velocity.

In the following, we neglect the energy loses for the mirror sector and thus take that its energy density rescales as $\rho \propto g_{\ast T} T^4$. We assume also that energy transferred to the mirror sector is conserved, i.e.

$$\frac{d}{dt}(\rho' R^3) + p' \frac{d}{dt}(R^3) = \Gamma_\epsilon R^3 n_e \langle E \rangle,$$

(8)

where $\langle E \rangle$ is the average energy transferred to the mirror sector per an $e\bar{e} \rightarrow e'\bar{e'}$ process. Then by excluding the scale factor $R$ and substituting $n_e \langle E \rangle$ approximately by $\rho_e$ in a source term, we obtain

$$\frac{d\rho'}{dt} + 3H(\rho' + p') = \Gamma_\epsilon \rho_e$$

(9)

where $\rho'$ and $p'$ are respectively the total energy density and the total pressure of the mirror sector: $p' \approx \rho'/3$ as far as the relativistic component is dominant. In our equation we only consider the energy transfer from ordinary to mirror sector without backreaction because the mirror energy density is smaller than the ordinary one by approximately a factor $x^4 \ll 1$ and hence the energy transfer from mirror to ordinary sector is negligible. The electron number density $n_e$ which enters in $\Gamma_\epsilon \rho_e$ (5) and the energy density $\rho_e$ are taken at their equilibrium values at the temperature $T$:

$$n_e(T) = \frac{2}{\pi^2} \int_{m_e}^{\infty} dE \frac{\sqrt{E^2 - m_e^2} E}{\exp(E/T) + 1}, \quad \rho_e(T) = \frac{2}{\pi^2} \int_{m_e}^{\infty} dE \frac{\sqrt{E^2 - m_e^2} E^2}{\exp(E/T) + 1}$$

(10)

Substituting $t = 0.3 M_P / g_{\ast T}^{1/2} T^2$, the above equation can be rewritten as

$$\frac{dp'}{dT} - 4\rho' T = -\epsilon^2 \frac{0.6 M_P}{\sqrt{g_{\ast T}}} \times \frac{\Gamma_1(T) \rho_e(T)}{T^3} \equiv -\epsilon^2 f_1(T)$$

(11)

and its solution can be presented as

$$\frac{\rho'(T)}{\rho(T)} = \epsilon^2 Q_T, \quad Q_T = -\frac{30}{\pi^2 g_{\ast T}} \int_{\infty}^{T} dy (f_1(y)/y^4)$$

(12)

where we assume that the energy of the mirror sector was negligible with respect to the ordinary one at the beginning. This is the most conservative initial condition: indeed if we assume that the energy of the mirror sector was comparable with the one of the ordinary sector, the bounds on $\epsilon$ become even more stringent.

The BBN bound on $\epsilon$ can be obtained solving this equation numerically and imposing that $\rho' / \rho = \epsilon^2 Q_T < 0.16 \Delta N_\nu$ at $T \approx 0.8$ MeV. On the other hand, for determining the cosmological bounds from the LSS and CMB, $x < 0.3$, one has to integrate eq. (12) till the temperatures $T \ll 1$ MeV. Our results for a function $Q_T$ are shown in Fig. [1]. We can see that below $T \approx 0.2$ MeV, $Q_T$ does not change anymore and it goes asymptotically to $Q_0 \approx 8 \times 10^{16}$. Physically this is due to Boltzmann suppression of the electron and positron densities below $T \approx m_e$, that leads to strong suppression of the energy transfer from the ordinary to the mirror sector. As we see,\footnote{This approximation of the exact Boltzmann equations leads to more conservative limits on $\epsilon$ as far as it underestimates the amount of the transferred energy.}
Figure 1: The parameter $Q_T = \epsilon^{-2}(\rho'/\rho)$ in units of $10^{18}$. It corresponds to the value of $\rho'/\rho$ for $\epsilon = 10^{-9}$.

The value of $Q_T$ at $T = 0.8$ MeV, relevant for the BBN epoch, is smaller roughly by a factor 2 than the asymptotic value $Q_0$.

Therefore, at the BBN epoch, $T \simeq 0.8$ MeV, we obtain the following bound:

$$
\epsilon < \sqrt{\frac{(\rho'/\rho)_{\text{BBN}}}{Q_{T=0.8\text{MeV}}}} \approx 1.5 \times 10^{-9} \left( \frac{\Delta N_\nu}{0.5} \right)^{1/2}
$$

(13)

The cosmological bound $x < 0.3$ or so concerns the temperature ratio $x = T'/T$ rather then the ratio of the densities $\rho'/\rho$. Taking that at $T \ll 1$ MeV we have $\rho(T) \propto g_* T^4$, with $g_\ast T \simeq 3$ that apart of the photons takes into account also the contribution of neutrinos decoupled from the thermal bath at the temperatures $T > 2$ MeV, while $\rho'(T) \propto g'_\ast T', T'^4$, with $g'_\ast T' = 2$ as contributed only by mirror photons since the mirror neutrinos cannot be produced at lower temperatures, we get the limit

$$
\epsilon < \sqrt{\frac{g'_\ast T'/g_* T}{Q_0}} x^2 < 3 \times 10^{-10} \left( \frac{x}{0.3} \right)^2
$$

(14)

Thus, a conservative cosmological bound requiring that $T'/T < 0.3$ at the Matter-Radiation equality epoch gives $\epsilon < 3 \times 10^{-10}$, while the galaxy formation bound $x < 0.2$ would give $\epsilon < 2 \times 10^{-10}$ about twice stronger limit.\(^8\) The interpretation [25] of the DAMA/Libra results in terms of Rutherford scattering of mirror baryons on ordinary matter is hardly compatible with these cosmological bounds on $\epsilon$, since then it requires the mass fraction of mirror oxygen $\xi_{O'}$ of about 0.6, which seems too much. The primordial chemical composition in mirror sector is not the same as in ordinary one [27] and thus also the present element abundances are presumably

\(^8\) Let us recall that this bound is valid only if dark matter is entirely constituted by mirror baryons.
different. So a detailed analysis of the stellar evolution may be performed (see e.g. in [29]) to calculate what should be the present concentration of oxygen. Nevertheless it seems hard to obtain such a high value. Finally, we stress that assuming \(x \sim 0.25\) leads to \(\xi_{O'} \sim 1\), that is, the mirror sector should be exclusively made of oxygen.

### 3 The asymmetric mirror model and dark matter

Cosmological observations indicate that the present universe is nearly flat, with the total energy density \(\rho_{\text{tot}}\) very close to the critical \(\rho_c\): \(\Omega_{\text{tot}} \equiv \frac{\rho_{\text{tot}}}{\rho_c} \simeq 1\). Non-relativistic matter in the universe consists of a baryonic (B) and a dark (DM) component where \(\Omega_{\text{DM}} \sim 0.21\) and \(\Omega_B \sim 0.04\) [18]. The relationship \(\Omega_{\text{DM}}/\Omega_B \sim 5\) is puzzling (fine tuning problem) since both \(\rho_B\) and \(\rho_{\text{DM}}\) scale as \(a^{-3}\) during the universe expansion and thus their ratio is independent on time. So a priori there is no apparent reason by which they should be so close to each other.

An answer to this problem is naturally found in the mirror sector physics, in particular if we assume that the mirror parity is broken, as it was suggested in [6, 9]. Indeed, we stated in the introduction that the mirror parity implies that the mass spectrum and the interaction properties are the same in the two sectors. Nevertheless, if mirror parity is spontaneously broken, the electroweak symmetry breaking scales are different in the ordinary and in the mirror sector and this would lead to different physics in the two sectors. In particular, if we call the Higgs expectation values in the ordinary and in the mirror sector respectively \(\langle \phi \rangle = v\) and \(\langle \phi' \rangle = v'\), we can define the parameter \(\zeta = v'/v\) and see immediately that the mass spectrum of elementary fermions \(f\) (leptons or quarks) and gauge bosons \(W, Z\) changes according to \(m_f/m_f' = \zeta\) and \(M_{W,Z}/M'_{W,Z} = \zeta\) [9]. At the same time the \(\Lambda_{\text{QCD}}\) constant scales according to \(\Lambda'/\Lambda = \zeta^{0.28}\) [30]. Hence, if we assume e.g. \(\zeta \sim 100\), the mirror electron mass scales up to \(m'_e \sim 50\) MeV while the (composite) masses of mirror nucleons become approximately \(M'_{B} \sim 5\) GeV that account for the scaling both of \(\Lambda' \sim 3.5\Lambda\) and of the light quark masses \(m'_{u,d} \sim 10^2 m_{u,d}\) [17].

Let us now analyze what are the cosmological bounds on the kinetic mixing parameter \(\epsilon\) in the asymmetric mirror scenario. The scattering \(e^+e^- \leftrightarrow e'^+e'^-\) is again the only relevant process and has a threshold at energy of order \(T_{\text{thr}} \sim m_e = \zeta m_e\) when ordinary electrons are still relativistic. Hence we can use the relativistic approximation for \(\Gamma\) in eq.(5) and solve analytically eq.(12), which gives

\[
\frac{\rho'(T)}{\rho(T)} = 7.7 \times 10^{-7} \epsilon^2 \frac{M_P}{\zeta m_e} \leq 0.16 \Delta N_\nu
\]

that implies \(\epsilon \leq 2 \times 10^{-8} \sqrt{\xi \Delta N_\nu/50}\). In the asymmetric case the bound on \(x\) from CMB does not apply: as far as \(m'_e \gg m_e\), mirror photons decouple much before the matter radiation equality epoch even if two sectors have the same temperatures, and thus mirror dark matter should behave practically as a cold dark matter, as far as the large scale structure and the CMB oscillations are concerned. Thus the only constraint comes from the BBN limit on the number of extra-neutrinos which we conservatively take as \(\Delta N_\nu \leq 0.5\) [9], which e.g. for \(\zeta = 100\) or \(m'_e = 50\) MeV, transforms in the bound \(\epsilon \leq 2 \times 10^{-8}\).

Let us recall, that according to ref. [25], elastic scattering of a mirror nucleus mediated by photon-mirror photon kinetic mixing gives best fit to the DAMA annual
modulation when its mass is of about 16 GeV. In the case of exact mirror parity, when the ordinary and mirror nucleons are exactly degenerate in mass, the proper mirror nucleus would be the oxygen, having \( M_{O'} \sim 16 \text{ GeV} \) and atomic number \( Z_{O'} = 8 \). On the other hand, in the case of asymmetric mirror (shadow) sector, with \( v'/v \sim 10^2 \), when mirror nucleons become about 4-5 times heavier than their ordinary brothers, the best candidate would be mirror helium, with mass \( M_{He'} \sim 16 \text{ GeV} \) and atomic number \( Z_{He'} = 2 \).

Since the interaction rate in DAMA is proportional to \((Z\epsilon)^2\xi\)\(,\) we need \(\epsilon\) about to be 4 times higher to compensate the charge difference between mirror helium and oxygen, that is \(\epsilon \sim 4 \times 10^{-9}\), which is compatible with our cosmological bound.

Nevertheless, it should be considered that in the asymmetric sector the mass difference between light quarks scales as \((m_{d'} - m_{u'}) \sim \zeta (m_d - m_u)\) and consequently the mass difference between the mirror neutron and proton is some hundred MeV, while \(\Lambda'_\text{QCD} \sim \zeta^0.3\Lambda_{\text{QCD}}\). Such a large mass difference cannot be compensated by the nuclear binding energy. Hence in the asymmetric mirror model also the neutrons bounded in nuclei may be unstable against \(\beta\) decay \([9]\) and thus heavy nuclei may be not formed. Obviously, in this case mirror helium will not exist as a stable nucleus, and the only possible candidate for dark matter can be the mirror hydrogen, with mass of about 4-5 GeV, which still can be appropriate for the DAMA/LIBRA signals, but the fit is much worse. In the supersymmetric extensions, if the parameters characterizing the up-down Higgs VEV ratios are not equal between two sectors, if \(\tan \beta' > \tan \beta\), than there is also possibility that the neutron rather than proton is the stable baryon in the mirror sector. In this case no mirror electrons and protons will be present in the present universe while dark matter will be due to mirror neutrons, and so practically no interesting limit can be settled for the photon-mirror photon kinetic mixing. However, in this case the latter mixing cannot be at work for the dark matter direct detection.

4 Conclusion

We have discussed cosmological implications of the parallel mirror world with the same microphysics as the ordinary one but having smaller temperature and the photon kinetically mixed with the ordinary one. In this model charged mirror particles acquire small electric charges (nanocharges) proportional to the mixing parameter \(\epsilon\).

In particular if mirror baryons are nanocharged, \(\epsilon \sim 10^{-9}\), the scattering of mirror nuclei on the standard matter may produce the annual modulations observed by the DAMA/LIBRA experiment and be at the same time avoid the (un)detection limits from other experiments looking for dark matter, such as CDMS and XENON 10 \([25]\). Actually the interaction rate does not depend simply on \(\epsilon\), but also on the mass fraction of oxygen \(\xi_{O'}\) and on its charge \(Z_{O'} = 8\) and is proportional to \((\epsilon Z)^2\xi_{O'}\).

Since \(\epsilon \sim 10^{-9}\) corresponds to \(\xi_{O'} \sim 0.1\), smaller values of \(\epsilon\) can be allowed if the amount of oxygen is higher than 0.1.

In this paper we have studied in detail the energy transfer from the ordinary to the mirror sector in order to calculate cosmological bounds on the kinetic mixing parameter \(\epsilon\) at the BBN and CMB epochs. When the mirror electrons are at least as heavy as the ordinary ones the pair annihilation of ordinary \(e\bar{e}\) in \(e'\bar{e'}\) is the only process by which there is a relevant energy transfer. We integrated the cross section at low energy in order to take into account the energy transfer below \(T \sim 1\) MeV,
which should be considered when imposing bounds from CMB. Our most conservative result is $\epsilon \leq 3 \times 10^{-10}$, which may be compatible with DAMA assuming $\xi_{O'} \sim 1$, which seems however an unnatural composition.

The cosmological bound on $\epsilon$ was calculated also in the asymmetric mirror model, where all particles are heavier than their ordinary partners [6]. Under this hypothesis the most conservative bound is $\epsilon \leq 2 \times 10^{-8}$, corresponding to 0.5 extra-neutrinos at the BBN epoch, while the more stringent cosmological bound coming from the LSS and CMB pattern does not apply in this case. In the asymmetric mirror model the best candidate to fit DAMA is helium, with $Z' = 2$, which requires a value of $\epsilon$ compatible with the above limit. A problem can however arise: the light quarks mass difference scales as the ratio of the Higgs VEVs in the two sectors, $\zeta = v'/v \sim 100$ and so does the neutron-proton mass difference, while $\Lambda_{QCD}$ scales as $\zeta^{0.3}$ [30]. Hence the nuclear binding energy may be not high enough to make bound neutrons stable. This problem should be further investigated in future researches.

**Note added** In the case of exact mirror parity, our limit on $\epsilon$ is somewhat stronger than the one obtained in the recent work [31].

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