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Unbroken versus broken mirror world: a tale of two vacua

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Abstract: If the lagrangian of nature respects parity invariance then there are two distinct possibilities: either parity is unbroken by the vacuum or it is spontaneously broken. We examine the two simplest phenomenologically consistent gauge models which have unbroken and spontaneously broken parity symmetries, respectively. These two models have a lagrangian of the same form, but a different parameter range is chosen in the Higgs potential. They both predict the existence of dark matter and can explain the MACHO events. However, the models predict quite different neutrino physics. Although both have light mirror (effectively sterile) neutrinos, the ordinary-mirror neutrino mixing angles are unobservably tiny in the broken parity case. The minimal broken parity model therefore cannot simultaneously explain the solar, atmospheric and LSND data. By contrast, the unbroken parity version can explain all of the neutrino anomalies. Furthermore, we argue that the unbroken case provides the most natural explanation of the neutrino physics anomalies (irrespective of whether evidence from the LSND experiment is included) because of its characteristic maximal mixing prediction.

Keywords: Beyond Standard Model, Neutrino Physics, Cosmology of Theories beyond the SM, Physics of the Early Universe.

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1. Introduction

Parity is a natural candidate for a symmetry in particle physics. The fact that experiments have established the $V - A$ nature of the weak interactions does not mean that parity cannot be a symmetry of the vacuum. This is due to there being no unique definition of the parity transformation in quantum field theory. Parity, by definition, takes $\vec{r}$ to $-\vec{r}$ and it also transforms left-handed fermion fields to right-handed fermions fields. However, since there are many left- and right-handed fermion fields, there is no unique definition. It is certainly true, though, that the standard model has no definition of parity which can be a symmetry of its lagrangian. Thus, if parity is a symmetry of the lagrangian of nature, new physics must exist.

It was realised some time ago that the simplest phenomenologically consistent gauge model with both a parity symmetric lagrangian and vacuum could be constructed by postulating the existence of a mirror sector [1] (see also ref. [2]). The idea was discussed earlier, before the advent of gauge theories, in ref. [3] and some cosmological implications were considered in refs. [4, 5, 6].

Suppose that for each known particle there exists a corresponding mirror particle. The mirror particles interact with other mirror particles in the same way that the ordinary particles interact with the other ordinary particles, except that mirror weak interactions are right-handed $(V + A)$ instead of left-handed $(V - A)$. The doubling of the particle spectrum which parity invariance suggests is not particularly radical in the historical context of particle physics. In particular the repetitive generation structure, the existence of antiparticles and the colour tripling of quarks are all familiar examples. Of these examples, Dirac's prediction of antiparticles from the requirement of Lorentz invariance is perhaps most analogous to the prediction of mirror particles from parity invariance (parity being an improper Lorentz transformation). Although the number of particles is doubled, it turns out that the number of parameters increases by only two (in the minimal version), making it the simplest (non-trivial) known extension to the standard model.

It turns out that in the minimal model, which has one Higgs doublet and one mirror Higgs doublet, the Higgs potential allows two non-trivial minima [7]. One minimum leaves parity unbroken by the vacuum, and the other has it spontaneously broken. The purpose of this paper is to compare and contrast the physics resulting from the two different vacuum solutions (which effectively can be considered two different theories). Both theories are phenomenologically consistent and are therefore possible extensions to the standard model. The mirror atoms/baryons in both cases provide plausible candidates for the dark matter in the universe. However, neutrino physics should be able to distinguish the two theories as we will show.

2. The lagrangian and the two vacua

Let us begin by briefly reviewing the model (for full details see ref. [1]). Consider the minimal standard model lagrangian $\mathcal{L}_1$. This lagrangian is not invariant under the usual parity transformation so it seems parity is violated. However, this lagrangian may not be complete. If we add to $\mathcal{L}_1$ a new lagrangian $\mathcal{L}_2$ which is just like $\mathcal{L}_1$ except that all left-handed (right-handed) fermions are replaced by new right-handed (left-handed) fermions which feel new interactions of the same form and strength, then the theory described by $\mathcal{L} = \mathcal{L}_1 + \mathcal{L}_2$ is invariant under a parity symmetry which induces $\mathcal{L}_1 \leftrightarrow \mathcal{L}_2$. In addition to these lagrangian terms, there may also be parity invariant terms which couple or mix ordinary matter with mirror matter. We label this part of the lagrangian as $\mathcal{L}_{\rm int}$. The terms in $\mathcal{L}_{\rm int}$ are very important since they lead to non-gravitational interactions between ordinary and mirror matter and hence allow the idea to be experimentally tested in the laboratory. These terms also contain the only new parameters of the model. In the minimal case, only two terms exist in $\mathcal{L}_{\rm int}$ because of the constraints of gauge invariance, parity invariance and renormalisablility. For this reason the minimal model has only two new parameters beyond those of the minimal standard model.

The gauge symmetry of the theory is[1]

$$\mathrm{SU}(3) \otimes \mathrm{SU}(2) \otimes \mathrm{U}(1) \otimes \mathrm{SU}(3)' \otimes \mathrm{SU}(2)' \otimes \mathrm{U}(1)' . \tag{2.1}$$

[1]Of course, grand unified alternatives such as SU(5) ⊗ SU(5), SO(10) ⊗ SO(10) and so on are also possible. Such alternatives predict similar low energy physics (see for example refs. [2, 8]). The idea may also be compatible with string theory ($E_8 \otimes E_8$) and with large extra dimensions [9].

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There are two sets of fermions, the ordinary particles (denoted without primes in the following) and their mirror images — the mirror particles (denoted with primes). The fields transform under the gauge group of eq. (2.1) as

$$\begin{aligned} f_L &\sim (1,2,-1)(1,1,0)\,, & f'_R &\sim (1,1,0)(1,2,-1)\,,\\ e_R &\sim (1,1,-2)(1,1,0)\,, & e'_L &\sim (1,1,0)(1,1,-2)\,,\\ q_L &\sim (3,2,1/3)(1,1,0)\,, & q'_R &\sim (1,1,0)(3,2,1/3)\,,\\ u_R &\sim (3,1,4/3)(1,1,0)\,, & u'_L &\sim (1,1,0)(3,1,4/3)\,,\\ d_R &\sim (3,1,-2/3)(1,1,0)\,, & d'_L &\sim (1,1,0)(3,1,-2/3)\,, \end{aligned} \tag{2.2}$$

with generation indices suppressed. The lagrangian is invariant under the discrete $\mathbb{Z}_2$ parity symmetry defined by[2]

$$\begin{gathered} \vec{r} \longrightarrow -\vec{r}\,, \qquad t \longrightarrow t\,,\\ G^\mu \longleftrightarrow G'_\mu\,, \qquad W^\mu \longleftrightarrow W'_\mu\,, \qquad B^\mu \longleftrightarrow B'_\mu\,,\\ f_L \longleftrightarrow \gamma_0 f'_R\,, \quad e_R \longleftrightarrow \gamma_0 e'_L\,, \quad q_L \longleftrightarrow \gamma_0 q'_R\,, \quad u_R \longleftrightarrow \gamma_0 u'_L\,, \quad d_R \longleftrightarrow \gamma_0 d'_L\,, \end{gathered} \tag{2.3}$$

where G^μ (G'^μ), W^μ (W'^μ) and B^μ (B'^μ) are the gauge bosons of the SU(3) (SU(3)$'$), SU(2) (SU(2)$'$) and U(1) (U(1)$'$) gauge forces, respectively. The minimal model contains two Higgs doublets,

$$\phi \sim (1,2,1)(1,1,0)\,, \qquad \phi' \sim (1,1,0)(1,2,1)\,, \tag{2.4}$$

which are also parity partners.

The most general renormalisable Higgs potential can be written in the form

$$V(\phi,\phi') = \lambda_+ \left(\phi^\dagger\phi + \phi'^\dagger\phi' - 2u^2\right)^2 + \lambda_- \left(\phi^\dagger\phi - \phi'^\dagger\phi'\right)^2\,, \tag{2.5}$$

where $\lambda_\pm$ and u^2 are real parameters. This Higgs potential furnishes only two vacua when $u^2 > 0$. For the region of parameter space defined by $\lambda_\pm > 0$ the vacuum expectation values (VEVs) of ϕ and ϕ' are equal and so parity is unbroken. (With the Higgs potential written in the above form this is manifest because the potential is non negative, and equal to zero for this vacuum solution.) Gauge invariance allows us to write the vacuum in the form

$$\langle\phi\rangle = \langle\phi'\rangle = \begin{pmatrix} 0 \\ u \end{pmatrix}. \tag{2.6}$$

Interestingly, a simple analysis shows that there is a qualitatively different minimum which occurs in the region of parameter space defined by

$$\lambda_+ + \lambda_- > 0 \qquad \text{and} \qquad \lambda_- < 0\,. \tag{2.7}$$

[2]By virtue of standard CPT invariance the theory also possesses time reversal invariance (which can be defined to be the product of the above parity transformation with the usual CPT transformation) [1]. The theory is therefore invariant under the full Poincaré group, including all improper Lorentz transformations.

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The vacuum solution now has one VEV non zero and the other zero [7]. In this region of parameter space, parity is broken spontaneously. This can be made manifest by rewriting the Higgs potential in terms of the parameters $\lambda_1 \equiv \lambda_+ + \lambda_-$ and $\lambda_2 \equiv -4\lambda_-$,

$$V(\phi, \phi') = \lambda_1 \left(\phi^\dagger \phi + \phi'^\dagger \phi' - u_B^2\right)^2 + \lambda_2 \left(\phi^\dagger \phi \phi'^\dagger \phi'\right), \tag{2.8}$$

where

$$u_B^2 \equiv \frac{2\lambda_+ u^2}{\lambda_+ + \lambda_-}. \tag{2.9}$$

Written in this way, for $\lambda_{1,2} > 0$, the vacuum solution

$$\langle \phi \rangle = u_B, \qquad \langle \phi' \rangle = 0, \tag{2.10}$$

or

$$\langle \phi \rangle = 0, \qquad \langle \phi' \rangle = u_B, \tag{2.11}$$

is manifest since the Higgs potential is non negative, and equal to zero for these two degenerate vacua. In the spontaneously broken parity model we adopt the solution of eq. (2.10) for definiteness. Notice that the parameters must be adjusted to make u and u_B both numerically equal to the observed electroweak symmetry breaking VEV (but not simultaneously, of course).

Let us examine the mirror particle spectrum of these two theories. In the unbroken mirror model (the one with the vacuum of eq. (2.6)) all of the mirror fermions and mirror gauge bosons have the same mass as the corresponding ordinary fermions and gauge bosons.

In the broken mirror model (the one with the vacuum of eq. (2.10)) it seems that the mirror fermions and the mirror gauge bosons are all massless because they all couple to ϕ' which has a vanishing VEV. However, dynamical effects from mirror QCD induced condensation will induce a small mass for the mirror weak bosons, W' and Z', as well as a tiny VEV for ϕ', and hence tiny masses for the mirror fermions. The latter effect is induced by the Yukawa coupling terms $h_q \overline{q}'_R q'_L \phi' +$ h.c., where h_q is the Yukawa coupling constant for quark flavour q. Mirror QCD interactions cause the mirror quark bilinears to have non-zero vacuum expectation values: $\langle \overline{q}' q' \rangle = \Lambda'^3$ where $\Lambda' \sim 100\,\mathrm{MeV}$ is the mirror QCD dynamical chiral symmetry breaking scale [7]. The resulting linear term in ϕ' effectively contributes to the Higgs potential so as to induce a small VEV, given by $\langle \phi' \rangle \simeq h_t \Lambda'^3 / m_{\phi'}^2$. Note that the largest contribution to the linear term comes from mirror top quark condensation due to the relatively large Yukawa coupling constant h_t. Further details have been given in ref. [7].

The result is the following particle spectrum:

- The W' and Z' bosons will have masses of order $\Lambda' \sim 100\,\mathrm{MeV}$.
- The four physical mirror scalars (two complex scalars ϕ'^+ and ϕ'^0) will be approximately degenerate with mass $\sqrt{\lambda_2}\, u_B$.

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- The mirror fermions ψ' will have masses given by

$$m_{\psi'} = k m_{\psi}\,, \quad \text{where} \quad k \equiv \frac{\langle\phi'\rangle}{\langle\phi\rangle} \sim \frac{g^2}{2}\frac{m_t \Lambda'^3}{m_W^2 m_{\phi'}^2}\,,$$

where g is the SU(2) gauge coupling constant, m_W is the ordinary W-boson mass, and m_ψ is the mass of the corresponding ordinary fermion ψ. Using the rough estimates $g^2 \sim 10^{-1}$, $m_t \sim m_W \sim 10^2\,\text{GeV}$ and $\Lambda' \sim 0.1\,\text{GeV}$, we see that $k \sim 10^{-6}(\text{GeV}/m_{\phi'})^2$. For example, if $m_{\phi'} \sim 10^2\,\text{GeV}$, then $k \sim 10^{-10}$. This means that the masses of the mirror fermions can range from about 10 eV for the mirror top-quark to 10^{-4} eV for the mirror electron. As this example illustrates, we expect k to be quite small ($\lesssim 10^{-10}$). Its precise value, however, cannot be specified because $m_{\phi'}$ depends on the free parameter λ_2.

3. Phenomenology

If the solar system is dominated by the ordinary particles (and this is expected theoretically as we will discuss shortly), then both of these theories agree with present experiments. (An extension to incorporate non-zero neutrino masses and mixings must be performed to get agreement with the neutrino deficit experiments.) These ideas can be tested in the laboratory because of the terms in $\mathcal{L}_{\text{int}}$. In the simplest case that we are considering at the moment (where $\mathcal{L}_1$ is the minimal standard model lagrangian), there are just two gauge and parity invariant and renormalisable terms in $\mathcal{L}_{\text{int}}$. They are: the Higgs potential term

$$2(\lambda_+ - \lambda_-)\phi^\dagger\phi\,\phi'^\dagger\phi' \tag{3.1}$$

contained within eq. (2.5), and the gauge boson kinetic mixing term

$$\omega F_{\mu\nu}F'^{\mu\nu}\,, \tag{3.2}$$

where $F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ is the field strength tensor for the U(1) gauge boson, and $F'_{\mu\nu}$ is its mirror analogue.

The main phenomenological effect of the term in eq. (3.1) is to modify the interactions of the Higgs boson. This effect will be tested if or when a Higgs boson is discovered. For the unbroken case, the implications of the Higgs mixing term have been discussed in refs. [1, 10, 11]. In the spontaneously broken case, the ordinary physical neutral Higgs boson H couples via cubic and quartic terms to the mirror Higgs doublet ϕ':

$$\mathcal{L}_{H\phi'} = 2\sqrt{2}\left(\lambda_1 + \frac{1}{2}\lambda_2\right) u_B H\phi'^\dagger\phi' + \left(\lambda_1 + \frac{1}{2}\lambda_2\right) H^2\phi'^\dagger\phi'\,. \tag{3.3}$$

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An experimental lower bound can be derived for λ_1 by observing that

$$\lambda_1 = \frac{m_H}{2u_B} \gtrsim 0.2\,, \tag{3.4}$$

where the experimental lower bound on the standard model Higgs boson mass of roughly 90 GeV has been used. This bound is valid even if H decays invisibly [12] into mirror matter (via $H \to \phi'^\dagger\phi'$). Thus the cubic and quartic ordinary — mirror Higgs interactions are necessarily quite large in the spontaneously broken model since λ_2, being a positive quantity, cannot be fine-tuned to make $\lambda_1 + (1/2)\lambda_2 \simeq 0$. It is also interesting to observe that there is no ordinary — mirror Higgs mass mixing in the spontaneously broken model. These remarks will be important when we discuss cosmological implications below.

The main phenomenological effect of the kinetic mixing term in eq. (3.2) is to give small electric charges to the mirror partners of the ordinary charged fermions [1, 2, 13]. In the case where the parity symmetry is unbroken, photon — mirror photon kinetic mixing leads to orthopositronium — mirror orthopositronium oscillations [2]. There is interesting evidence that these oscillations have actually been observed experimentally [14]. However, this tantalising result needs experimental confirmation.

If neutrinos are massive, then this will allow an important window on the mirror world which was first realised in 1991 [10]. This is because $\mathcal{L}_{\rm int}$ can contain neutrino mass terms which mix the ordinary and mirror matter.[3] A remarkable, but very simple, result is that if ordinary and mirror neutrinos mix at all then the resulting neutrino oscillations must be maximal if the parity symmetry is unbroken [10, 15]. To see this consider the electron neutrino. If there is no mirror matter, and if intergenerational mixing is small as in the quark sector, then the weak eigenstate electron neutrino is approximately a single mass eigenstate. However if mirror matter exists, then there will be a mirror electron neutrino ν'_e. The most general mass matrix consistent with parity conservation (eq. (5)) is

$$\mathcal{L}_{\rm mass} = [\bar{\nu}_e, \bar{\nu}'_e] \begin{pmatrix} m & m' \\ m' & m \end{pmatrix} \begin{bmatrix} \nu_e \\ \nu'_e \end{bmatrix} + \text{h.c.}\,, \tag{3.5}$$

where the masses can be taken as real without loss of generality. This mass matrix has the above form whether the neutrinos are Majorana or Dirac states. Diagonalising, we easily obtain that the weak eigenstates ν_e and ν'_e are each maximally mixed combinations of mass eigenstates:

$$\nu_e = \frac{(\nu_1^+ + \nu_1^-)}{\sqrt{2}}\,, \qquad \nu'_e = \frac{(\nu_1^+ - \nu_1^-)}{\sqrt{2}}\,, \tag{3.6}$$

where ν_1^+ and ν_1^- are the mass eigenstates. Thus, the effect of ordinary matter mixing with mirror matter is very dramatic. No matter how small (or large) the

[3] Note that if electric and mirror electric charges are conserved, then it is not possible for $\mathcal{L}_{\rm int}$ to contain mass terms mixing the charged fermions of ordinary matter with those of mirror matter.

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mass interaction term is, the mixing is maximal. This result immediately leads to a beautiful and natural explanation of the neutrino physics anomalies [10, 15]: the solar anomaly is due to maximal $\nu_e \to \nu'_e$ oscillations, the atmospheric anomaly is due to maximal $\nu_\mu \to \nu'_\mu$ oscillations, while the LSND anomaly can be accomodated through small intergenerational mixing between the first and second families. Maximal mixing can be considered a "smoking gun" for unbroken parity invariance in nature!

For the broken parity case, the maximal mixing feature between the ordinary and mirror neutrinos is completely lost. In fact, the mixing angles between any ordinary neutrino and its mirror partner will be suppressed by the tiny parameter $k \equiv \langle\phi'\rangle/\langle\phi\rangle$. To see this, it is simplest to think in terms of effective operators. At the dimension-5 level the relevant terms are

$$\mathcal{L}_{\text{eff}} = \frac{a}{M}\left[\overline{f}_L\phi^c\ \phi^\dagger(f_L)^c + \overline{f'}_R\phi'^c\ \phi'^\dagger(f'_R)^c\right] + \frac{b}{M}\overline{f}_L\phi^c\ (\phi'^c)^\dagger f'_R + \text{h.c.}\,, \tag{3.7}$$

where M is a high scale, perhaps the seesaw scale. The resulting effective low energy Majorana mass matrix yields a mixing angle of order k.[4]

So, although the minimal broken mirror model provides a nice rationale for light effectively sterile neutrinos, then can play no observable role in neutrino phenomenology! In particular, the solar, atmospheric and LSND anomalies cannot be simultaneously resolved. Furthermore, the possible scenarios for explaining the solar and atmospheric results involve the ordinary neutrinos only, and thus have no novel features. The predictivity of the unbroken mirror model for neutrino physics is totally absent in the broken version.

4. Astrophysics and cosmology

In both theories, the lightest mirror baryon is stable and provides a natural candidate for the inferred dark matter of the universe. Mirror matter will behave like cold dark matter on large scales, but the self interactions will modify the physics on small scales. In the unbroken case, the interactions and masses of the mirror particles are completely analogous to the ordinary particles. The lightest mirror baryon in this case is, of course, the mirror proton. This case has been studied in refs. [4, 5, 16] where it was argued that the mirror particles provide a plausible candidate for the dark matter of the universe. It was also shown that the mirror matter may be segregated from ordinary matter on distance scales much larger than the solar system but may be well mixed on the scale of galaxies. Interestingly, there is observational evidence that some of the dark matter in our galaxy is in the form of invisible stars. This evidence comes from the MACHO candidates obtained from the microlensing observations of stars in the Large Magellanic Cloud [17]. These observations are consistent with the existence of mirror matter since mirror matter

[4]One of the authors (RRV) thanks K.S. Babu for emphasising this point in conversation.

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naturally forms star mass sized objects [18]. There are also a number of other interesting cosmological implications of the unbroken mirror world which are discussed in ref. [19].

In the spontaneously broken mirror model, we expect the lightest mirror baryon to be (mirror) electrically neutral. We will call it the mirror neutron. It is the lightest mirror baryon because the mirror up quark — down quark mass difference is negligible ($\ll$ eV), so the mirror proton — mirror neutron mass difference is dominated by the electromagnetic corrections. This means that the mirror proton would be expected to be a few MeV *heavier* than the mirror neutron. Thus, mirror neutrons would be stable and form the mirror dark matter. In the broken model, the mirror pions will have very small mass $\sim \sqrt{k}m_\pi \lesssim 1\,\mathrm{keV}$. This will significantly increase the range of the mirror strong interactions. In view of this it seems quite plausible that the interactions of the mirror neutrons of the spontaneously broken mirror model will be strong enough and dissipative enough to cause the collapse of a mirror neutron gas into mirror stars/planets and the like. The spontaneously broken model may therefore also explain the mysterious MACHO population inferred from the microlensing observations (although perhaps not quite as naturally as the unbroken model).

Of course, observations suggest that the amount of cold dark matter needed may be significantly greater than the amount of ordinary baryons in the universe. This feature is not inconsistent with an exact mirror symmetry when one realises that microscopic symmetries do not always lead to macroscopic symmetries. Thus, the number of mirror baryons in the universe need not be exactly the same as the number of ordinary baryons even if the microscopic parity symmetry is unbroken. It is, however, most plausible for the number of mirror baryons in the universe to be of the same order of magnitude as the number of ordinary baryons. On the other hand, the moderately successful Big Bang Nucleosynthesis (BBN) predictions suggest that the temperature of the mirror plasma was somewhat lower (a factor of two would suffice) than the temperature of the ordinary plasma during the BBN epoch. The temperature difference between the ordinary and mirror matter can be ascribed to unknown physics at early times or simply as an initialy condition. Specific mechanisms based on inflation have been studied in refs. [5, 16, 20].

Of course for consistency it is important that the non-gravitational interactions between the ordinary and mirror particles be small enough so that they do not populate the mirror sector and wipe out the temperature difference. We will consider in turn the three generic effects of $\mathcal{L}_{\rm int}$: photon — mirror photon kinetic mixing, neutrino — mirror neutrino mass mixing, and Higgs boson — mirror Higgs boson interactions and mixing.

A stringent constraint from BBN was derived some years ago on the photon — mirror photon kinetic mixing parameter ω, $\omega \lesssim 3 \times 10^{-8}$ [6], and was recently re-examined in [21]. Little more needs to be said about this here. One should note, though, that the orthopositronium — mirror orthopositronium resolution of

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the orthopositronium anomaly requires a kinetic mixing parameter $\omega \sim 5\times 10^{-7}$ [14], which violates this bound. Should this proposed resolution be confirmed by future experiments, then standard BBN would apparently need to be modified in some way.

A much more stringent astrophysical bound on the kinetic mixing parameter holds for the broken mirror model. Plasmon states in red giant stars would be expected to decay into mirror fermion — mirror antifermion pairs, because all the charged mirror fermions are very light in this case. This would produce unexpectably rapid cooling if ω were larger than about 10^{-14} [22, 21].

The BBN bounds on neutrino to mirror neutrino oscillations in the symmetric mirror model have been discussed at length in the literature [23]. The important point is that large relic neutrino asymmetries will be generated by ordinary to mirror oscillations (just as for ordinary to sterile oscillations) [24] provided that the oscillation parameters are in the appropriate range. The large asymmetries can then suppress mirror neutrino production because the matter effect depresses the effective mixing angle [25]. In the broken mirror model, mirror neutrino production is automatically very suppressed by the tiny mixing angles whose origin was explained above.

We now need to derive consequences for BBN due to Higgs boson — mirror Higgs boson coupling and mixing. The consequences actually depend on cosmology at temperature scales much higher than those of BBN. It is simplest to discuss this issue within the context of inflationary cosmology, even though the existence of an inflationary epoch has yet to be observationally established. Suppose first of all that the reheating temperature $T_{\rm RH}$ of the ordinary plasma was at least several hundred GeV. Recall that inflationary scenarios can be constructed to provide asymmetric reheating for the ordinary and mirror plasmas: $T'_{\rm RH} < T_{\rm RH}$ [5, 16, 20]. Will subsequent ordinary — mirror Higgs interactions force the mirror plasma temperature T' to equal the ordinary plasma temperature T? In this case, electroweak symmetry is presumably restored and the ordinary Higgs doublet ϕ is a component of the ordinary plasma. The relevant process to consider is therefore $\phi^*\phi \to \phi'^*\phi'$ scattering. If we want the rate for this scattering process to be less than the expansion rate of the universe for all temperatures above the phase transition temperature, the stringent constraint [8, 26],

$$\lambda_+ - \lambda_- \equiv \lambda_1 + \frac{1}{2}\lambda_2 \lesssim 3\times 10^{-6}\sqrt{\frac{m_\phi}{\rm TeV}}\,, \qquad (4.1)$$

must be satisfied. For the symmetric mirror model, this constraint can be met by requiring the two positive parameters λ_+ and λ_- to almost cancel.[5] Once this has been done, the bound of eq. (4.1) also suffices to prevent ordinary — mirror plasma

[5]This is actually technically natural because the combination $\lambda_+ - \lambda_-$ is just the coupling between the ordinary and mirror scalars which if zero would increase the symmetry of the theory (separate global Lorentz groups for the ordinary and mirror sectors).

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thermal equilibration by Higgs boson processes occurring after electroweak symmetry breakdown. For the broken mirror model, this constraint can never be satisfied, because λ_2 is positive and λ_1 is bounded from below as per eq. (3.4). Thus, if $T_{\rm RH}$ is higher than the Higgs boson mass scale, then the ordinary and mirror plasmas must come to thermal equilibrium, making the model incompatible with standard BBN.

The relevance of the bound in eq. (4.1) was recently re-examined in ref. [11] for the symmetric mirror model case. It was pointed out that the $T_{\rm RH}$ could be much lower than the electroweak phase transition temperature. If so, then the bound in eq. (4.1) is irrelevant. Instead, a weaker bound pertains which arises from Higgs boson — mirror Higgs boson mass mixing after symmetry breaking. See ref. [11] for full details, and in particular for a discussion of the dramatic Higgs boson phenomenology that could be discovered by the Large Hadron Collider if this scenario is correct.

Using similar reasoning, the broken mirror case can be made compatible with BBN if the reheating temperature is less than the Higgs boson mass scale. However, after the electroweak phase transition[6] the cubic term in eq. (3.3) will induce the process

$$b\,\overline{b} \longrightarrow t'\,\overline{t}'\,t'\,\overline{t}'\,. \tag{4.2}$$

Using dimensional analysis, the rate for this process is

$$\Gamma = a\left(\lambda_1 + \frac{1}{2}\lambda_2\right)^2 h_t^4 \frac{m_b^2}{m_H^4 m_{\phi'}^8} T^{11}\,, \tag{4.3}$$

where a is a numerical factor expected to be in the range 0.1–10. Requiring this rate to be less than the expansion rate $\mathcal{H} \sim T^2/M_{\rm P}$, where $M_{\rm P}$ is the Planck mass, we obtain the rough bound

$$\lambda_1 + \frac{1}{2}\lambda_2 \lesssim \frac{m_H^2 m_{\phi'}^4}{h_t^2 m_b \sqrt{M_{\rm P}}} T_{\rm RH}^{-9/2} \sim 100\left(\frac{m_\phi}{100\,\mathrm{GeV}}\right)^6 \left(\frac{T_{\rm RH}}{\mathrm{GeV}}\right)^{-9/2}, \tag{4.4}$$

where m_ϕ is now a generic Higgs or mirror Higgs boson mass scale. We see that the bound is quite weak for reasonable m_ϕ with the reheating temperature in the 10's of GeV range.

As our final comment on the cosmology of the broken mirror model, we address the issue of a possible domain wall problem [27]. Superficially, it appears that this model, like other models with spontaneously broken discrete symmetries, would present a serious domain wall problem if the electroweak phase transition actually took place. This potential problem can be easily solved by postulating a reheating temperature which is lower than the critical temperature of the putative electroweak phase transition ($T_{\rm RH} < T_{\rm EW} \sim 100\,\mathrm{GeV}$). It is also interesting to observe that no domain wall problem would arise for this particular model even for reheating temperatures in the range $T_{\rm EW} < T_{\rm RH} < m_\phi$. This is because of our expectation that the

[6]Note that this phase transition can be eliminated by having a sufficiently low $T_{\rm RH}$.

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ordinary and mirror plasmas should have different temperatures in order to achieve successful BBN. The asymmetric temperatures would cause asymmetric finite temperature corrections to the Higgs potential. Although the two parity breaking vacua would be degenerate at zero temperature, they would not be degenerate for any finite T and T' if $T \neq T'$. The energy density differential between the domains on either side of a wall would induce a pressure that would be easily large enough (for a T'/T value consistent with BBN) to cause the wall to rapidly collapse (see ref. [28] for a general discussion of domain wall collapse due to energy density bias). Because of the bound in eq. (4.1), the reheating temperature must still be constrained to be less than m_ϕ, otherwise $T' < T$ cannot hold at lower temperatures.

5. Next-to-minimal broken mirror model

Several years after the unbroken and spontaneously broken mirror models were introduced, another type of mirror model was discussed in ref. [29] (and some cosmological implications discussed in ref. [30]). These authors modified the minimal models [1, 7] discussed here by postulating an additional scalar particle. This allows $k \equiv \langle\phi'\rangle/\langle\phi\rangle$ to be a free parameter [29], in contrast to both the unbroken and broken incarnations of the minimal model. While this model is distinct from the minimal mirror models, it is not quite as predictive because it is has more free parameters (especially the mirror symmetry breaking scale). It has also been used to address the neutrino problems, (with the $\nu_e \to \nu_s$ small angle MSW solution [31] to the solar neutrino problem and $\nu_\mu \to \nu_\tau$ solution to the atmospheric neutrino anomaly) [29], as well as the dark matter and MACHO problems [18].

6. Concluding remarks

The hypothesis of mirror matter allows one to write down a phenomenologically tenable gauge model with parity (and in fact the full Poincaré group) as an exact symmetry of both the lagrangian and the vacuum state of nature [1]. Interestingly, the same lagrangian supplies also a parity asymmetric vacuum state for a certain range of parameters [7]. The phenomenology, astrophysics and cosmology of both incarnations of the minimal mirror model have been examined in this paper.

One of the most urgent tests of these ideas lies with neutrino physics. The unbroken or symmetric mirror model features maximally mixed pairs of ordinary and mirror neutrinos [10, 15]. For terrestrial experiments, mirror neutrinos are effectively sterile states. The most natural solution to the atmospheric neutrino anomaly uses maximal $\nu_\mu \to \nu'_\mu$ oscillations, while the solar neutrino anomaly is most attractively solved through maximal $\nu_e \to \nu'_e$ oscillations [10, 15]. From an experimental perspective, this is a combined maximal $\nu_\mu \to \nu_s$ and $\nu_e \to \nu'_s$ scenario. While neither of these solutions currently provide a perfect fit to the experimental data, they are

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broadly consistent with the atmospheric [32] and solar experiments [33]. Observe that if it turns out that the atmospheric neutrino anomaly is due to $\nu_\mu \to \nu_\tau$ oscillations then this, by itself, cannot rule out the unbroken mirror matter model. It just means that the $\nu_\mu \to \nu'_\mu$ oscillation length — which is controlled by a free Δm^2 parameter — is much greater than $10,000$ km for atmospheric neutrino energies relevant to the experiments.

The forthcoming neutral current measurement from SNO will be a crucial test of the $\nu_e \to \nu'_e$ solution to the solar neutrino problem. Efforts to discriminate between the $\nu_\mu \to \nu_s$ and $\nu_\mu \to \nu_\tau$ solutions to the atmospheric neutrino anomaly, both from the MINOS and CERN — Gran Sasso long baseline experiments and possibly from SuperKamiokande itself, will also be important. While SuperKamiokande claims to disfavour the $\nu_\mu \to \nu_s$ or ν'_μ solution [34], we have to wait for a detailed account of their analysis procedure in order to judge the robustness of this conclusion. The Miniboone experiment will also be important, because its ability to check the LSND result [35] will also confirm or disconfirm the latter's indirect evidence for a light sterile neutrino. If the participation of a light sterile state in the neutrino anomalies is confirmed by future data, then the minimal *broken* mirror model will certainly be ruled out.

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