Discovering mirror particles at the Large Hadron Collider and the implied cold universe

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Abstract

The Mirror Matter or Exact Parity Model sees every standard particle, including the physical neutral Higgs boson, paired with a parity partner. The unbroken parity symmetry forces the mass eigenstate Higgs bosons to be maximal mixtures of the ordinary and mirror Higgs bosons. Each of these mass eigenstates will therefore decay 50% of the time into invisible mirror particles, providing a clear and interesting signature for the Large Hadron Collider (LHC) which could thus establish the existence of the mirror world. However, for this effect to be observable the mass difference between the two eigenstates must be sufficiently large. In this paper, we study cosmological constraints from Big Bang Nucleosynthesis on the mass difference parameter. We find that the temperature of the radiation dominated (RD) phase of the universe should never have exceeded a few 10's of GeV if the mass difference is to be observable at the LHC. Chaotic inflation with very inefficient reheating provides an example of how such a cosmology could arise. We conclude that the LHC could thus discover the mirror world and simultaneously establish an upper bound on the temperature of the RD phase of the universe.

I. INTRODUCTION

The Mirror Matter or Exact Parity Model (EPM) sees every standard particle paired with a parity partner. This idea was first mentioned by Lee and Yang in their seminal paper on parity violation \[1\] as a way to retain the full Poincaré Group as a symmetry of nature despite the \(V - A\) character of weak interactions. Some follow up work was
performed in the ensuing decades on some aspects of the mirror matter hypothesis [2]. In 1991, the idea was independently rediscovered and the full gauge theory constructed for the first time [3]. Shortly thereafter the EPM was extended to include nonzero neutrino masses and mixings and applied to the solar, atmospheric and LSND anomalies [4,5]. The EPM can also alter standard Big Bang cosmology in interesting ways, through the possible identification of some dark matter with mirror matter, and through modifications of Big Bang Nucleosynthesis (BBN) [6].

The ordinary and mirror particle sectors can interact in a number of ways. The first is through gravitation, with immediate consequences for the dark matter problem and astrophysics. Non-gravitational interactions can be induced through the mixing of colourless and neutral particles with their mirror counterparts. Neutrinos, the photon, the $Z$ boson and the physical neutral Higgs boson can mix with the corresponding mirror states. Coloured and/or electrically charged particles are prevented from mixing with their mirror analogues by colour and electric charge conservation laws.

The purpose of this paper is to study the Higgs boson sector of the EPM. It has been previously noted that the mass eigenstate physical Higgs bosons must be maximal mixtures of the underlying ordinary and mirror states because of the unbroken parity symmetry [3,4]. Each mass eigenstate will therefore decay 50% of the time into invisible mirror particles, providing a striking experimental signature in principle. The production cross-section for such Higgs bosons would be 1/2 of that of the standard Higgs boson of the same mass. This is a very simple and important observation, because it provides a clear way to experimentally establish the existence of the mirror world [1]. In recent years there has been a strong focus on using the neutrino anomalies as a way to discover mirror matter [4–6]. Neutrino oscillation physics certainly does provide a very interesting way to garner experimental evidence for mirror matter, or to at least constrain the model (if one is being pessimistic). However, the terrestrial neutrino phenomenology of the EPM is similar to that of pseudo-Dirac neutrinos [8], so complementary information would be useful. The Higgs boson sector is one potentially important way to obtain this information. (The mixing of ortho-positronium with mirror-ortho-positronium is another [9].)

The strength of Higgs boson mixing with its mirror partner is controlled by an a priori independent dimensionless parameter $\lambda_{HH'}$. The mass splitting between the mass eigenstate Higgs bosons is proportional to this same parameter. Standard cosmology, through BBN, can be used to constrain $\lambda_{HH'}$ and hence the Higgs boson mass splitting also [10]. In this paper, we will demonstrate that the temperature of the radiation dominated (RD) phase of the universe should never have exceeded a few tens of GeV if the mass splitting is to be substantial (of order 1 GeV). Chaotic inflation with very inefficient reheating is an example of how such a cold cosmology could arise. Remarkably, the Large Hadron Collider (LHC) could thus discover the mirror world as a byproduct of its Higgs boson search programme, and simultaneously establish an upper bound on the temperature of the RD phase of the universe.

\[1\] From the recent results of the L3 Collaboration [7] we can establish a lower bound of about 65 GeV for a Higgs boson with these properties.
II. THE HIGGS BOSON SECTOR AND COSMOLOGICAL CONSTRAINTS

Consider a minimal Higgs boson sector for the EPM. It contains the standard Higgs doublet $\phi$, transforming as a $2(1)$ representation under the electroweak gauge group $SU(2) \otimes U(1)_Y$. It also contains a mirror Higgs doublet $\phi'$ which transforms as a $2(1)$ representation under the mirror electroweak gauge group $SU(2)' \otimes U(1)'_Y$. The standard doublet $\phi$ is a singlet under the mirror gauge group, while $\phi'$ is a singlet under the ordinary gauge group. Under the discrete parity symmetry, $\phi \leftrightarrow \phi'$.

We focus on the Higgs potential in this paper. It is very simply given by

$$V = \lambda (\phi^\dagger \phi + \phi'^\dagger \phi' - 2v^2) + \lambda_-(\phi^\dagger \phi - \phi'^\dagger \phi')^2.$$  \hspace{1cm} (1)

In the $\lambda_+ > 0$ region of parameter space, the vacuum is clearly given by

$$\langle \phi \rangle = \langle \phi' \rangle = \left( \begin{array}{c} 0 \\ v \end{array} \right).$$  \hspace{1cm} (2)

In this region of parameter space, the parity or mirror symmetry is respected by the vacuum because of the equality between the vacuum expectation values (VEVs) of the ordinary and mirror Higgs doublets.\footnote{A parity breaking global minimum of this Higgs potential can be found in another region of parameter space \cite{11}.}

Going to unitary gauge and shifting the neutral components as per $\phi^0 = v + H/\sqrt{2}$ and $\phi'^0 = v + H'/\sqrt{2}$ we see from Eq.(1) that the mass eigenstates are

$$H_\pm = \frac{H \pm H'}{\sqrt{2}}$$ \hspace{1cm} (3)

with masses given by

$$m_+^2 = 8\lambda_+ v^2 \quad \text{and} \quad m_-^2 = 8\lambda_- v^2$$ \hspace{1cm} (4)

respectively. We therefore see that the mass splitting

$$\Delta m \equiv m_+ - m_- = (\lambda_+ - \lambda_-) \frac{8v^2}{m_+ + m_-}$$ \hspace{1cm} (5)

is controlled by the parameter

$$\lambda_{HH'} \equiv \lambda_+ - \lambda_-.$$ \hspace{1cm} (6)

From Eq.(1) we also see that the coefficient of the $HH'$ mixing term, $4\lambda_{HH'} v^2$, is proportional to the same parameter. In addition, the coefficient of the quartic coupling term $\phi^\dagger \phi \phi'^\dagger \phi'$ is $2\lambda_{HH'}$.

It is clear that each mass eigenstate physical neutral Higgs boson $H_\pm$ decays 50% of the time into ordinary particles and 50% of the time into mirror, and hence invisible, particles.
The total decay rate of $H_+$ or $H_-$ is the same as that for a SM physical neutral Higgs boson of the same mass. Note also that each mass eigenstate couples to ordinary particles with strength reduced by $1/\sqrt{2}$ compared to the coupling of the standard Higgs boson to those same particles.

We now turn to cosmological constraints from BBN on $\lambda_{HH'}$, or equivalently, $\Delta m$. BBN does not allow the mirror plasma to be in thermal equilibrium with the ordinary plasma during the relevant epoch. The parameters controlling the mixing of colourless and neutral particles with their mirror partners must therefore obey upper bounds, assuming that the standard theory of BBN is correct. The derivations of these bounds for the photon and neutrino systems have been described elsewhere.

The Higgs system situation was briefly discussed in Ref. and will be fully explored here. There are two different epochs to consider: (i) temperatures $T \gtrsim 100$'s of GeV, where the Higgs bosons exist as real particles in the plasma, and (ii) the opposite limit where they do not.

Epoch (i) was considered in Ref.. The physics is very simple. Suppose that no mirror particles exist in the plasma to begin with. We then have to ensure that processes driven by $\lambda_{HH'}$ do not bring the mirror Higgs bosons, and hence all other mirror particles, into thermal equilibrium. During epoch (i), the electroweak symmetry is presumably restored, so the relevant term is $2\lambda_{HH'}\phi^\dagger\phi\phi'^\dagger\phi'$ from the Higgs potential. By dimensional analysis, the rate for $\phi\phi \rightarrow \phi'\phi'$ scattering will be approximately given by $(\lambda_{HH'})^2T$. Requiring that this be less than the expansion rate of the universe $\simeq \sqrt{gT^2/m_P}$, where $g \simeq 100$ is the effective number of massless degrees of freedom and $m_P$ is the Planck mass, we find the bound

$$\lambda_{HH'} \lesssim 10^{-8} \left(\frac{m_\phi}{100\text{GeV}}\right)^{1/2}.$$  

(7)

This bound is obtained by setting the temperature $T$ to be about $m_\phi$ in order to get the most restrictive condition, where $m_\phi \simeq 100$’s of GeV is the Higgs mass in the symmetric phase. This is clearly a severe bound. If the assumptions behind its derivation were unassailable, then the EPM would have a significant fine-tuning problem: why is $\lambda_{HH'}$ so small? It has been observed that the supersymmetric extension of the EPM yields $\lambda_{HH'} = 0$. While this is of interest, we will look for an alternative solution, because $\lambda_{HH'} = 0$ eliminates the chance for the LHC to discover the mirror world. For a sufficiently small $\Delta m$, the ordinary particles from which the Higgs bosons are produced yield a coherent superposition of $H_+$ and $H_-$ which is precisely the ordinary Higgs boson $H$. The Higgs physics of the EPM is then indistinguishable from that of the Standard Model. According to Ref., the LHC is expected to measure the Higgs boson mass with an accuracy of roughly 1%. This means that $\lambda_{HH'}$ must be larger than about 0.01 for the mass difference between $H_+$ and $H_-$ to be observable.

So, let us suppose that the radiation dominated phase of the universe was never hot enough for Higgs bosons to exist as real particles in the plasma! The bound of Eq.(7) is then irrelevant. Such a “cold universe” can be produced, for example, by inefficient reheating after inflation. We will discuss this further in the next section.

For $T \ll m_\phi$, mirror particles can be brought into thermal equilibrium via the $f\bar{f} \rightarrow f'\bar{f}'$ process mediated by virtual Higgs boson exchange as depicted in the Figure. We will also
take \( T \) to be less than the temperature for the electroweak phase transition (about 100 GeV), so we are in the broken phase. The rate is given roughly by

\[
\Gamma \sim h_f^4 \lambda_{HH'}^2 \frac{v^4 T^5}{m_\phi^8},
\]  

(8)

where \( h_f = m_f/v \) is the Yukawa coupling constant for the fermions and mirror fermions in the initial and final states. For \( T \ll 100 \) GeV, top quarks are not a significant component of the plasma, so the bottom quark \( b \bar{b} \to b' \bar{b}' \) process will dominate all others. We therefore set \( h_f = h_b = m_b/v \). The condition that \( \Gamma \) is always less than the expansion rate then implies that

\[
\lambda_{HH'} \lesssim \frac{m_\phi^4 g^{1/4}}{m_b^2 \sqrt{m_T}} \simeq 0.1 \left( \frac{T_{\text{max}}}{\text{GeV}} \right)^{-\frac{2}{3}} \left( \frac{m_\phi}{200 \text{GeV}} \right)^4.
\]  

(9)

which is most restrictive for the highest temperature \( T_{\text{max}} \) we hypothesise the radiation dominated phase of the universe to reach. If we require that the Higgs boson mass difference be observable at the LHC \( (\lambda_{HH'} \sim 0.01) \) then \( T_{\text{max}} \) cannot be higher than a few tens of GeV. Furthermore, if \( T_{\text{max}} \) does not exceed a few GeV then \( \lambda_{HH'} \sim 1 \) is allowed.

The cold universe hypothesis simultaneously remedies the \( \lambda_{HH'} \) fine-tuning problem, and allows a large mass splitting between \( H_+ \) and \( H_- \). Remarkably, the LHC could simultaneously discover the mirror world and produce strong evidence that the RD phase of the universe was never hotter than a few tens of GeV!

### III. COLD COSMOLOGY?

We will now make a few remarks about how such a cold cosmology could be constructed. As well as providing a low \( T_{\text{max}} \), the cosmological model would also have to explain why the early universe was predominantly composed of ordinary matter in the first place. A universe with an ordinary and mirror plasma in thermal equilibrium with each other is ruled out by BBN. Phrased another way, we must require that the temperature \( T' \) of the mirror plasma be less than about half of the temperature of the ordinary plasma during the BBN epoch in order for the expansion rate of the universe to not be too high.

The \( T' \) issue has already been addressed in the literature through inflationary models \[15,16\]. As an example, Ref. \[16\] introduces an inflaton \( \sigma \) and a mirror inflaton \( \sigma' \) with the potential

\[
U = \frac{1}{2} m^2 (\sigma^2 + \sigma'^2)
\]  

(10)

If \( T_{\text{max}} \) is below \( m_b \simeq 4.4 \) GeV, then charmed quarks and tau leptons should be used instead of bottom quarks.

[3]
in the context of the chaotic inflationary paradigm (see, e.g. [17]). They then suppose that the chaotic initial conditions set up \( \sigma' \ll \sigma \) by chance. The equations of motion derived from \( U \) then show that \( \sigma'/\sigma \) remains constant during the inflationary phase. This means that the \( \sigma' \) field will begin oscillating about \( \sigma' = 0 \) while \( \sigma \) is still driving inflation. Assuming further that \( \sigma' (\sigma) \) couples only to mirror (ordinary) particles, the reheated mirror plasma created by the decays of \( \sigma' \) gets diluted by the inflationary expansion that is still occurring. When \( \sigma \) subsequently ceases driving inflation, it then produces a reheated ordinary plasma that has a much higher temperature than the diluted mirror plasma. All we need to further postulate is very inefficient reheating to produce the required cold universe. One will ultimately also need a baryogenesis mechanism that can work at such low temperatures. Some proposals already exist in the literature, including the exploitation of the pre-heating process for this purpose [18].

The above is but an example of how a cold cosmology with asymmetric temperatures for the ordinary and mirror plasmas might arise. Many other issues need to be addressed, including the origin of the inflaton potential, the precise mechanism of reheating, and whether a substantial (but still subdominant) amount of mirror matter can be produced in addition to the ordinary matter during re- or pre-heating (as would be needed for mirror dark matter purposes). For the moment, our focus should be on the interesting and simple Higgs physics of the EPM. If the LHC discovers a large mass splitting between \( H_+ \) and \( H_- \), then this terrestrially obtained data will provide good motivation for further work in cosmological model building.

**IV. CONCLUSIONS**

The Exact Parity or Mirror Model predicts some simple and interesting Higgs physics. There will be two physical neutral Higgs boson mass eigenstates, each with a 50% invisible width. This would be a remarkable way to discover mirror particles. A detectable mass splitting between the two eigenstates would strongly suggest that the radiation dominated phase of the universe was never hotter than, say, a few tens of GeV. This would in turn be interesting information for cosmological model builders.

**ACKNOWLEDGMENTS**

We would like to thank Nicole Bell and Sergei Gninenko for discussions and Robert Foot for comments on a draft manuscript. A.I. is grateful to D.Grigoriev and M.Shaposhnikov for helpful discussions. This work was supported by the Australian Research Council.

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This important idea illustrates how a cosmology which is asymmetric between the ordinary and mirror sectors can arise despite the identical microphysics: exploit fluctuations.
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Diagram of the process $f f \rightarrow f' f'$ mediated by Higgs–mirror-Higgs boson mixing.