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SEVEN (AND A HALF) REASONS TO BELIEVE IN MIRROR MATTER: FROM NEUTRINO PUZZLES TO THE INFERRED DARK MATTER IN THE UNIVERSE

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Parity and time reversal are obvious and plausible candidates for fundamental symmetries of nature. Hypothesising that these symmetries exist implies the existence of a new form of matter, called mirror matter. The mirror matter theory (or exact parity model) makes four main predictions: (1) Dark matter in the form of mirror matter should exist in the Universe (*i.e.* mirror galaxies, stars, planets, meteoroids ...), (2) Maximal ordinary neutrino–mirror neutrino oscillations if neutrinos have mass, (3) Orthopositronium should have a shorter effective lifetime than predicted by QED (in "vacuum" experiments) because of the effects of photon–mirror photon mixing and (4) Higgs production and decay rate should be 50% lower than in the standard model due to Higgs mirror–Higgs mixing (assuming that the separation of the Higgs masses is larger than their decay widths). At the present time there is strong experimental/observational evidence supporting the first three of these predictions, while the fourth one is not tested yet because the Higgs boson, predicted in the standard model of particle physics, is yet to be found. This experimental/observational evidence is rich and varied ranging from the atmospheric and solar neutrino deficits, MACHO gravitational micro-lensing events, strange properties of extrasolar planets, the existence of "isolated" planets, orthopositronium lifetime anomaly, Tunguska and other strange "meteor" events including perhaps, the origin of the moon. The purpose of this article is to provide a not too technical review of these ideas along with some new results.

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1. Introduction

One thing that physicists have learned over the years is that the interactions of elementary particles obey a variety of symmetries. Some of these symmetries are quite familiar such as rotational invariance and translational invariance — physics text books are the same in Melbourne as they are in Moscow (once you translate them!). There are also other, less familiar symmetries such as gauge invariance and (proper) Lorentz invariance, which are nevertheless quite elegant and natural once you get to know them. Of course, it is pertinent to recall that the invariance of particle interactions under these symmetries was not always so obvious. For example, Dirac showed us that the (quantum mechanical) interactions of the electron were only compatible with (proper) Lorentz invariance if positrons (*i.e.* anti-matter) existed. Fortunately for Dirac, his startling prediction was soon verified by experiments.

Remarkably though, experiments in the 1950's and 1960's showed that space reflection symmetry (parity) and time reflection symmetry (time reversal) do not appear to be fundamental symmetries of particle interactions. For example, in well known beta decay processes, such as $p \to n + e^+ + \nu_e$, the electron neutrinos[1], ν_e *always* have their spin angular momentum aligned opposite to their direction of motion (similar to a "left handed" cork screw). Nobody has ever observed a "right handed" neutrino. However, just as (proper) Lorentz invariance required the existence of anti-matter, it turns out that it is possible for particle interactions to conserve also the improper Lorentz transformations of parity and time reversal if a new form of matter exists — mirror matter. In this theory [1], each ordinary particle, such as the photon, electron, proton and neutron, has a corresponding mirror particle, of exactly the same mass as the ordinary particle. The parity symmetry interchanges the ordinary particles with the mirror particles [as well as $(x, y, z, t) \to (-x, -y, -z, t)$] so that the properties of the mirror particles completely mirror those of the ordinary particles[2]. For example the mirror proton and mirror electron are stable and interact with the mirror photon in the same way in which the ordinary proton and electron interacts with the ordinary photons. The mirror particles are not produced in laboratory experiments just because they couple very weakly to the ordinary particles. In the modern language of gauge theories, the mirror particles are all singlets under the standard $G \equiv \mathrm{SU(3)} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$ gauge interactions. Instead the mirror fermions interact with a set of mirror gauge particles, so that the gauge symmetry of the theory is doubled, *i.e.* $G \otimes G$ (the ordinary parti-

[1] The neutrino is a class of weakly interacting elementary particle with intrinsic spin $\frac{1}{2}$. High Energy Physics experiments have revealed that 3 different "species" of neutrino exist, called electron neutrinos (ν_e), muon neutrinos (ν_μ) and tau neutrinos (ν_τ).

[2] It also also possible to envisage variant theories for which the symmetry is broken so that the mirror particles have masses which are different from the ordinary particles. Such theories though, are typically more complicated and less predictive, as well as being less elegant. See Ref. [2] for a discussion of these variants. Also note that the mirror matter model is also compatible with many extensions of the standard model including: Grand Unification, Supersymmetry, Technicolour, Extra dimensions (large and small), Superstring theory (especially $E_8 \otimes E_8$) *etc.*

cles are, of course, singlets under the mirror gauge symmetry) [1]. Parity is conserved because the mirror particles experience right-handed mirror weak interactions while the ordinary particles experience the usual left-handed weak interactions. Ordinary and mirror particles interact with each other predominately by gravity only.

While parity is obviously an extremely attractive theoretical candidate for a symmetry of nature, its existence cannot, unfortunately, be proven by pure thought (well at least nobody has done so up to now). Whether or not nature is left–right symmetric will be decided by experiments. The mirror matter theory makes four main experimentally testable predictions:

- Mirror matter (*e.g.* mirror hydrogen composed of mirror protons and mirror electrons) should exist in the Universe and would appear to us as Dark Matter [3]. Specifically, mirror galaxies, mirror stars, mirror planets and perhaps even mirror meteoroids could all exist.
- If neutrinos are massive (and non-degenerate) then oscillations between ordinary and mirror neutrinos are maximal [4, 5].
- Orthopositronium should have a shorter effective lifetime ("vacuum" experiment) than predicted in QED due to the effects of photon–mirror photon kinetic mixing [6, 7].
- Higgs production and decay rate should be 50% lower than in the standard model of particle physics due to Higgs; mirror Higgs mixing [1, 4]. This holds assuming that the two mass eigenstate Higgs fields have mass separation much larger than their decay widths[3].

At the present time there is strong experimental/observational evidence supporting the first three of these predictions, while the fourth one is not tested yet because the Higgs boson, predicted in the standard model of particle physics, has yet to be found (though it may be found in collider experiments in the near future). This experimental/observational evidence can be viewed as an explanation to seven specific scientific puzzles (most of them long standing), which we list below:

(a) Massive Astrophysical Compact Halo Objects (MACHOs): Invisible star-sized objects in the halo of our galaxy identified by their gravitational effects in microlensing searches.

(b) Close-in extrasolar planets: Large gas giants only ~ 7 million kilometers (0.05 a.u.) from their star, where it is too hot for them to form.

[3] On the other hand, if the mass splitting is very small then there will be no experimentally observable mirror Higgs effect (see Ref. [8] for a detailed study).

(c) Recent discovery of "isolated planets" in the Sigma Orionis star cluster; the properties of these objects are unexplained by existing theories.

(d) Solar neutrino deficit: Half of the electron neutrinos emitted by nuclear reactions in the solar core are missing.

(e) Atmospheric neutrino deficit: Half of the (up-going) ν_μ produced as a consequence of cosmic ray interactions with the atmosphere are missing.

(f) Orthopositronium lifetime anomaly: A precision vacuum cavity experiment finds a lifetime shorter than the standard model prediction.

(g) Disappearing meteors: Tunguska (and Tunguska-like events) including, perhaps, the origin of the moon.

We now describe how the mirror matter theory explains these 7 scientific puzzles.

2. Implications of the mirror world for cosmology: MACHOs, extra-solar planets and "isolated planets" ((a), (b) & (c))

There is strong evidence for a large amount of exotic dark matter in the Universe (maybe as much as 95% of the mass of the Universe). For example, the orbits of stars at the (visible) edge of our galaxy provide information about the distribution of matter within our galaxy. These observations show that there must exist invisible halos in galaxies such as our own Milky Way. Furthermore, there is also strong evidence that this dark matter must be something exotic: ordinary matter simply cannot account for it [9]. Mirror matter is naturally dark (because the coupling of mirror matter to ordinary photons is necessarily very small[4]) and is a very natural candidate for the inferred dark matter in the Universe. This has been argued for some time by Blinnikov and Khlopov [3] (see also the recent reviews in [11]). The physics of galaxy formation in the early Universe is far from being completely understood. Phenomenologically, one envisages galaxies containing some mixture of ordinary and mirror matter. In fact just about anything is possible; galaxies ranging from no mirror matter, to galaxies composed almost entirely of mirror matter. Mirror matter inside galaxies will fragment into diffuse clouds and eventually into mirror stars. This type of collapse

[4] A very small coupling between ordinary and mirror photons is allowed by the theory and is suggested by an experiment measuring the orthopositronium lifetime (see Sec. 6) but this interactionis too small to make mirror matter directly observable [10].

should happen quite independently for ordinary and mirror matter, since they will have locally different initial conditions such as angular momentum and abundance as well as chemical composition[5]. Thus, dark matter made of mirror matter would have the property of clumping into compact bodies such as mirror stars, however, their distribution within the galaxy can be quite independent of the distribution of ordinary matter. Dark matter composed of mirror matter thus leads naturally to an explanation [12] for the mysterious massive astrophysical compact halo objects (or MACHO's) inferred by the MACHO collaboration [13]. This collaboration has been studying the nature of halo dark matter by using the gravitational microlensing technique. This Australian–American experiment has so far collected 5.7 years of data and has provided statistically strong evidence for dark matter in the form of invisible star sized objects which is what you would expect if there was a significant amount of mirror matter in our galaxy [12]. The MACHO collaboration [13] have done a maximum likelihood analysis which implies a MACHO halo fraction of 20% for a typical halo model with a 95% confidence interval of 8% to 50%. Their most likely MACHO mass is between $0.15\,M_\odot$ and $0.9\,M_\odot$ depending on the halo model. These observations are consistent with a mirror matter halo because the entire halo would not be expected to be in the form of mirror stars. Mirror gas and dust would also be expected because they are a necessary consequence of stellar evolution and should therefore significantly populate the halo.

If mirror matter does indeed exist in our galaxy, then binary systems consisting of ordinary and mirror matter should also exist. While systems containing approximately equal amounts of ordinary and mirror matter are unlikely due to the differing rates of collapse for ordinary and mirror matter (leading to a local segregation of ordinary and mirror matter), systems containing predominately ordinary matter with a small amount of mirror matter (and *vice versa*) should exist. Interestingly, there is remarkable evidence for the existence of such systems coming from extra-solar planet astronomy.

In the past few years more than 50 "extrasolar" planets have been discovered orbiting nearby stars [14]. They reveal their presence because their gravity tugs periodically on their parent stars leading to observable Doppler shifts. In one case, the planet HD209458b, has been observed to transit its star [15] allowing for an accurate determination of the size and mass for this system. One of the surprising characteristics of the extrasolar planets

[5] For example, the rate of collapse of mirror matter in a diffuse gas cloud will obviously occur at a different rate to ordinary matter in the cloud because collapse requires non-gravitational dissipative processes (such as atomic collisions) to release the energy so that the system can become more tightly bound. These dissipative processes will occur at different rates for ordinary and mirror matter due to their different initial conditions and chemical composition.

is that there are a class of large ($\sim$M$_{\rm Jupiter}$) close-in planets with a typical orbital radius of ~ 0.05 a.u., that is, about 8 times closer than the orbital radius of Mercury (so called "51 Pegasi-like" planets after the first such discovery [16]). Ordinary (gas giant) planets are not expected to form close to stars because the high temperatures do not allow them to form. Theories have been invented where they form far from the star where the temperature is much lower, and migrate towards the star. While such theories are possible, there are also difficulties, *e.g.* the recent discovery of a close-in pair of resonant planets [17] is unexpected since migration tends to make the separation between planets diverge (as the migration speeds up as the planet becomes closer to the star).

A fascinating alternative possibility presents itself in the mirror world hypothesis. The close-in extrasolar planets may be mirror worlds composed predominately of mirror matter [18]. They do not migrate significantly, but actually formed close to the star which is not a problem for mirror worlds because they are not significantly heated by the radiation from the star. This hypothesis can explain the opacity of the transiting planet HD209458b because mirror worlds would accrete ordinary matter from the solar wind which accumulates in the gravitational potential of the mirror world [19]. It turns out that the effective radius of ordinary matter depends relatively sensitively on the mass of the planet, so that this mirror world hypothesis can be tested when more transiting planets are discovered [19].

If this mirror world interpretation of the close-in extrasolar planets is correct then it is very natural that the dynamical mirror image system of a mirror star with an ordinary planet will also exist. Such a system would appear to ordinary observers as an "isolated" ordinary planet. Remarkably, such "isolated" planets have recently been identified in the σ Orionis star cluster [20]. These planets have estimated mass of 5–15 M$_{\rm Jupiter}$ (planets lighter than this mass range would be too faint to have been detected in Ref. [20]) and appear to be gas giants which do not seem to be associated with any visible star. Given that the σ Orionis cluster is estimated to be less than 5 million years old, the formation of these "isolated" planets must have occurred within this time (which means they can't orbit faint stellar bodies such as white dwarfs). Zapatero-Osorio *et al.* [20] argue that these findings pose a challenge to conventional theories of planet formation which are unable to explain the existence of numerous isolated planetary mass objects. Thus the existence of these planets is very surprising if they are made of ordinary matter, however, there existence is quite natural from the mirror world perspective [21]. Furthermore, if the isolated planets are not isolated but orbit mirror stars then there must exist a periodic Doppler shift detectable on the spectral lines from these planets. This represents a simple way of testing this hypothesis [21].

There is also recent, tantalizing observational evidence for mirror matter from another source; a recent weak gravitational microlensing study [22] has apparently discovered an invisible dark concentration of mass in the vicinity of the cluster, Abell 1942. A fascinating possibility is that a mirror galaxy (or galaxy cluster) containing virtually no ordinary matter has been discovered. Further studies (such as Ref. [23]) should help clarify whether this mirror matter interpretation is correct.

Finally, let us also mention that the existence of mirror matter may have interesting consequences for early Universe cosmology. However, early Universe cosmology is not precise enough yet to shed much light on mirror matter (although forthcoming precision measurements of the cosmic microwave background may help). For some recent articles on the implications of mirror matter for early Universe cosmology, see Ref. [24].

3. Implications of the mirror world for neutrino physics: solar and atmospheric neutrino deficits ((d) & (e))

It was realized in 1991 [4] and further studied in Ref. [5], that neutrino oscillations of ordinary neutrinos into mirror neutrinos would provide a simple way of testing the mirror world hypothesis. Neutrino oscillations are a well known quantum mechanical effect which arise when the flavour eigenstates are linear combinations of 2 or more mass eigenstates. For example, if the electron and muon neutrinos have mass which mixes the flavour eigenstates, then in general the weak eigenstates are orthogonal combinations of mass eigenstates, *i.e.*

$$\nu_e = \sin\theta \nu_1 + \cos\theta \nu_2, \qquad \nu_\mu = \cos\theta \nu_1 - \sin\theta \nu_2 \,. \tag{1}$$

A standard result is that the oscillation probability for a neutrino of energy E is then:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 L/L_{\rm osc} \,, \tag{2}$$

where L is the distance from the source and $L_{\rm osc} \equiv 4E/\delta m^2$ is the oscillation length (and natural units have been used, *i.e.* $c = h/2\pi = 1$) [6]. If $\sin^2 2\theta = 1$ then the oscillations have the greatest effect and this is called maximal oscillations. In our 1992 paper we found the remarkable result that the oscillations between ordinary and mirror neutrinos are necessarily maximal which is a direct consequence of the parity symmetry. One way to see this is to note that if neutrinos mix then the mass eigenstates are non-degenerate and necessarily parity eigenstates if parity is unbroken. Considering the electron

[6] In Eq. (2), $\delta m^2 \equiv m_1^2 - m_2^2$ is the difference in squared masses of the neutrino mass eigenstates.

neutrino, ν_e and its mirror partner, ν'_e, the parity eigenstates are simply $\nu^\pm = (\nu_e \pm \nu'_e)/\sqrt{2}$ (since parity interchanges the ordinary and the mirror particles) and hence:

$$\nu_e = \frac{\nu^+ + \nu^-}{\sqrt{2}}, \qquad \nu'_e = \frac{\nu^+ - \nu^-}{\sqrt{2}}. \tag{3}$$

Comparing this with Eq. (1) we see that $\theta = \pi/4$ *i.e.* $\sin 2\theta = 1$ and hence maximal mixing! Thus, if neutrinos and mirror neutrinos have mass and mix together then the oscillations between the ordinary and mirror neutrinos are necessarily maximal. This simple observation nicely explains the solar neutrino deficit since the oscillations between $\nu_e \to \nu'_e$ reduce the flux of ν_e from the Sun by a predicted 50% after averaging over energy and distance (provided of course that the oscillation length is less than the distance between the earth and the Sun, which means $\delta m^2 \lesssim 3 \times 10^{-10}$ eV^2) [7]. Electron neutrinos emitted from the Sun arise from various nuclear reactions in the solar core. Theoretically the most important are the *pp* reaction chain, where two protons fuse together to form deuterium: $p + p \to^2 \mathrm{H} + e^+ + \nu_e$. This neutrino flux can be most reliably predicted since it is directly related to the luminosity of the Sun. There are 3 experiments specifically designed to measure the *pp* neutrinos which are called SAGE, GALLEX and GNO. The SAGE and GALLEX experiments began running around 1991 with GNO starting in 1998. Their most recent results normalized to the theoretical prediction [26] are [27]:

$$\begin{aligned} 0.52 &\pm 0.06\,(\mathrm{exp}) \pm 0.05\,(\mathrm{theory}) \quad (\mathrm{SAGE}),\\ 0.59 &\pm 0.06\,(\mathrm{exp}) \pm 0.05\,(\mathrm{theory}) \quad (\mathrm{GALLEX}),\\ 0.50 &\pm 0.09\,(\mathrm{exp}) \pm 0.05\,(\mathrm{theory}) \quad (\mathrm{GNO}), \end{aligned} \tag{4}$$

where the errors are $1 - sigma$. These results are consistent with the mirror matter prediction of 0.5. More recently the SuperKamiokande Collaboration have reported an energy independent (within errors) recoil electron energy spectrum in their experiment designed to measure the ^{8}B neutrinos (*i.e.* neutrinos from the nuclear reaction, $^8\mathrm{B} + e^- \to {}^8_4\mathrm{Be} + \nu_e$), again finding only 50% of the expected solar flux. Again these results were predicted in the mirror matter model [4, 5].

During 1993 I first became aware of the atmospheric neutrino anomaly and immediately recognized that this could be further important evidence for mirror matter [5]. This anomaly suggests that the muon neutrino (ν_μ) oscillates into some other neutrino species with large mixing angle (which was only weakly constrained in 1993). This anomaly can easily be explained

[7] In principle it is necessary to take into account matter effects for neutrino propagation in the Sun and the Earth. However, the net effect is only a slight modification to the naive 50% ν_e flux reduction expected for vacuum oscillations (which may nevertheless be important in some circumstances) [25].

by the Mirror Matter model since, as we have discussed above, it predicts that each of the known neutrinos oscillates maximally with its mirror partner if neutrinos have mass. Thus in this case it is theoretically very natural to explain the atmospheric neutrino anomaly via $\nu_\mu \to \nu'_\mu$ oscillations (where ν'_μ is the mirror muon neutrino)[8]. With the new results from the SuperKamiokande experiment the prediction of maximal mixing has been confirmed with the 90% allowed region [29]

$$0.85 \lesssim \sin^2 2\theta \lesssim 1.0\,. \tag{5}$$

This is in nice agreement with the 1993 mirror matter prediction of $\sin^2 2\theta = 1$.

Of course, neutrino oscillations into the mirror world is not the only possible solution to the neutrino anomalies. However, it does provide an elegant explanation for the inferred maximal neutrino oscillations of ν_e (solar) and ν_μ (atmospheric) which is good reason to take it seriously[9]. Furthermore, it is one of the few solutions to the solar and atmospheric neutrino puzzles which is also consistent with the LSND accelerator experiment [32]. The LSND experiment provides strong evidence that mixing between at least the first two generations is small (which is already known to happen for quark mixing). Most importantly, the mirror world explanation will be tested more stringently in the near future from a variety of new experiments including Borexino [33], Kamland [34] and especially the Sudbury Neutrino Observatory (SNO) [35]. The latter experiment will be crucial in distinguishing $\nu_e \to \nu'_e$ oscillation solution to the solar neutrino problem with many other proposals, while Borexino and Kamland will be very important in pinning down the δm^2, $\sin^2 2\theta$ parameters (and in the process stringently checking the mirror world prediction of $\sin 2\theta = 1$).

4. Implications of the mirror world for laboratory experiments: orthopositronium lifetime anomaly ((f))

There are essentially only 3 ways in which ordinary and mirror matter can interact with each other besides gravity: that is by photon mirror photon kinetic mixing [1, 6, 36], Higgs; mirror Higgs interactions [1, 4], and by neutrino–mirror neutrino mass mixing (if neutrinos have mass) [4, 5][10].

8 Of course the main alternative case of $\nu_\mu \to \nu_\tau$ oscillations is also possible within this framework [28], but it doesn't seem to be quite so elegant.

9 These days it is often argued that [30] the solution to the atmospheric neutrino anomaly is $\nu_\mu \to \nu_\tau$ oscillations (and it may be), however, the SuperKamiokande data itself cannot yet distinguish the simplest mirror world explanation from $\nu_\mu \to \nu_\tau$ oscillations [31].

10 Only neutral particles can mix with each other sinceelectric charge is conserved. Mixing of say an electron with a mirror electron would violate electric charge conservation and such mixing is constrained to be negligible.

The effect of neutrino–mirror neutrino mass mixing has already been described; it leads to maximal ordinary-mirror neutrino oscillations which can simply and predictively explain the atmospheric and solar neutrino deficits. The effect of Higgs–mirror Higgs interactions is to reduce the production and decay rate by 50% compared with the standard model Higgs particle (provided that the Higgs mass splitting is large enough). This prediction will be tested when the Higgs is discovered which may occur soon either at Fermilab or at the Large Hadron Collider at CERN. Finally, we have photon–mirror photon kinetic mixing which leads to interesting effects for orthopositronium.

Photon–mirror photon kinetic mixing is described in quantum field theory as the Lagrangian term:

$$\mathcal{L}_{\rm int} = \frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} \,, \tag{6}$$

where $F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu$ is the usual field strength tensor, and the F' is the corresponding quantity for mirror photons. This Lagrangian term may be considered as a fundamental interaction of nature [1] or may arise as a quantum mechanical "radiative correction" effect [36] (see also Ref. [37]). Glashow [6] has shown that the kinetic mixing term leads to a modification of the orthopositronium lifetime (which turns out to be the most important experimental implication of photon–mirror photon kinetic mixing). Recall orthopositronium is the bound state composed of an electron and positron where the spins of both particles are aligned so that the bound state has spin 1. The ground state of orthopositronium (oPs) decays predominately into 3 photons. The decay rate has been computed in QED leading to a discrepancy with some of the experimental measurements. Some of the measurements find a faster decay rate than theoretically predicted. This discrepancy has lead to a number of experimental searches for exotic decay modes, including a stringent limit on invisible decay modes [38].

The modification of the lifetime predicted in the mirror matter theory occurs because the kinetic mixing of the photon with the mirror photon generates a small off-diagonal orthopositronium mass leading to oscillations between orthopositronium and mirror orthopositronium. The orthopositronium produced in the experiment oscillates into its mirror partner, whose decays into three mirror photons are undetected. This effect only occurs in a vacuum experiment where collisions of the orthopositronium with background particles can be neglected [39]. Collisions with background particles will destroy the quantum coherence necessary for oscillations to occur. Thus, experiments with large collision rates remain unaffected by kinetic mixing and the lifetime of orthopositronium will be the same as predicted by QED. Experiments in vacuum, on the other hand, should show a slight increase in the decay rate, as oscillations into mirror orthopositronium and their subsequent invisible decays effectively reduce the number of orthopositronium states faster than QED predicts. The two most accurate experimental results, normalized to the theoretical QED prediction [40] are given in the table below[11]. Thus, we see that the Tokyo experiment agrees with

TABLE I

Reference	$\Gamma_{\rm oPs}(\exp)/\Gamma_{\rm oPs}(\text{theory})$	Method	$\Gamma_{\rm coll}$
Ann Arbor [44]	1.0012 ± 0.0002	Vacuum cavity	$\sim(3-10)\Gamma_{\rm oPs}$
Tokyo [43]	1.0000 ± 0.0004	Powder	$\sim 10^4 \Gamma_{\rm oPs}$

the QED prediction while the Ann Arbor vacuum experiment disagrees by about 6 sigma. These results can be explained in the mirror matter model by observing that the large collision rate ($\Gamma_{\rm coll}$) of the orthopositronium in the Tokyo experiment will render oscillations of orthopositronium with its mirror counterpart ineffective[12], while the larger decay rate obtained in the vacuum cavity experiment can be explained because of the much lower collision rate of orthopositronium in this experiment allows the oscillations of ordinary to mirror orthopositronium to take effect. The fit of the theory to the cavity experiment implies that the kinetic mixing parameter is $\varepsilon \approx 10^{-6}$ [7].

While the mirror world can nicely explain the orthopositronium lifetime puzzle, this puzzle is based only on one anomalous vacuum cavity experiment (however the statistical significance is impressive: 6 sigma). Also, the value for ε is a bit too large to be acceptable for early Universe cosmology (BBN) unless of course, one of the standard assumptions is wrong (which is certainly possible of course)[13]. Clearly, what is really needed is a new experiment to

[11] A third experiment with gas [41] also has an anomalously high decay rate, however, there appears to be large possible systematic uncertainties because their are indications that the orthopositronium may not be thermalized (as assumed) in this experiment [42, 43].

[12] The experimental limit [38] for invisible decay modes also does not exclude this mirror world oscillation mechanism because the collision rate of the orthopositronium was very high in those experiments.

[13] Consistency with standard Big Bang Nucleosynthesis (BBN) suggests that $\varepsilon \lesssim 3\times10^{-8}$ [45]. However, the cosmological situation is by no means clear. For example, there are tentative indications from recent precision measurements of the cosmic microwave background that the energy density of the early Universe could be about a factor of two larger than expected given the standard particles (which is what you would expect if $\varepsilon \simeq 10^{-6}$ because the effects of the photon–mirror photon kinetic mixing interaction would then fully populate the mirror sector in the early Universe). Also there may exist a pre-existing or neutrino oscillation generated neutrino asymmetry which may further modify things [46].

check the anomalous vacuum cavity result. In fact, an experiment with a larger cavity should make things very clear, since there should be an even larger mirror world effect if $\varepsilon \approx 10^{-6}$. Such an experiment has been proposed to test for this effect and to confirm (or reject) the mirror world explanation for the orthopositronium lifetime anomaly [47].

5. Disappearing meteors: Tunguska (and Tunguska-like events) including, perhaps, the origin of the moon ((g))

To summarise the current situation, mirror matter is predicted to exist if nature is left–right symmetric (*i.e.* parity invariant). There is now considerable experimental/observational support for mirror matter coming from neutrino physics, the orthopositronium lifetime puzzle, and astrophysics/cosmology. It should be clear that further work in these fields can really put the predictions of the mirror matter to more stringent experimental/observational test.

Given the simplicity and appeal of the mirror matter theory and the large amount of experimental evidence in favour of it, it is tempting to entertain more fascinating (but also more speculative) implications of the theory. If mirror matter exists then perhaps one of the most fascinating possibilities is that there is significant (by this I simply mean enough to be "observable") amount of mirror matter in our solar system. While much of any initial mirror matter component in our solar system may have found its way into the center of the Sun[14] (where its effects are more difficult to be unambiguously observed) it is nevertheless possible for small mirror space bodies (such as mirror meteoroids or mirror comets *etc.*) could exist[15]. Such mirror bodies may not orbit in the same plane as the ecliptic — they may orbit in a different plane, or may be even spherically distributed (like the Oort cloud).

If such mirror bodies exist and happen to collide with the Earth, what would be the consequences? If the only force connecting mirror matter with ordinary matter is gravity, then the consequences would be minimal. The mirror space body would simply pass through the Earth and nobody would know about it unless the body was so heavy as to gravitationally affect the motion of the Earth. However, if there is kinetic mixing between ordinary and mirror photons (which is suggested by the orthopositronium experiment), then the mirror space body would heat up as the nuclei of the mirror

[14] Some may also be in the center of planets, but not so much. *E.g.* one can deduce an upper bound of about 10^{-3} for the fraction of mirror matter content of the Earth [48].

[15] It is also possible that a large mirror body such as a mirror planet/star might exist in our solar system if it is a relatively distant companion to the Sun [49,50].

atoms undergo Rutherford scattering as they weakly interact (made possible because of the photon–mirror photon kinetic mixing interaction, Eq. (6)) with the nuclei of the ordinary oxygen and nitrogen in the atmosphere. The ordinary matter which passes through the mirror meteoroid would also heat up as the mirror meteoroid moves through the Earth's atmosphere. This may make the mirror meteoroid effectively visible as it plumets to the surface of our planet. There are essentially two possibilities (depending on the chemical composition of the mirror meteoroid and also on the kinetic mixing parameter ε); either it disintegrates in the atmosphere or it survives to reach the Earth's surface. If it disintegrates no fragments will be found, since mirror matter would be undetectable in our ordinary matter surroundings. If it survives and enters the ground then two things can happen depending on the stopping distance (D). Either it is stopped over a short distance ($\lesssim 100\,\mathrm{m}$) in which case the energy of the impact should leave a crater, while if it is stopped over a large distance ($\gtrsim$ few kilometers) no impact crater would form since the meteoroid's kinetic energy would be distributed over a large distance. Again, in either case no meteoroid fragments would be found. It is straightforward to roughly estimate the stopping distance D, which depends on the strength of the kinetic mixing parameter ε, the initial velocity of the space body (v_i), and also (more weakly) on the chemical composition of the mirror space body and the density and composition of the ground where it enters the Earth's surface. A rough calculation of the stopping distance in the Earth's crust in the case of very small $\varepsilon \lesssim 10^{-8}$ (using the surface density of the Earth of $\rho \approx 3\,\mathrm{g/cm}^3$) gives[16]:

$$D \sim \left(\frac{v_i}{30\ \mathrm{km}/s}\right)^4 \left(\frac{10^{-9}}{\varepsilon}\right)^2\ \mathrm{km}\,. \tag{7}$$

Thus, for $\varepsilon \lesssim 10^{-9}$, the typical stopping distance in the Earth's crust is greater than about a kilometer. Thus, such a body would *not* be expected to leave a large crater while for much larger values of ε, such as the value suggested by the orthopositronium experiment ($\varepsilon \simeq 10^{-6}$), the mirror meteoroid would release most of its kinetic energy in the atmosphere, leading perhaps to an atmospheric explosion. Remarkably there appears to be significant evidence for "disappearing meteors" [51], *i.e.* meteors which are seen but do not lead to any impact crater and no meteor fragments are found. The most famous such event is the 1908 Siberian explosion (the "Tunguska event"). The cause of this and other such events has remained unclear and is the source of many debates (with frequent conferences) [52]. It is certainly remarkable that the fireball which has been presumed to be an ordinary asteroid or comet simply disappears without trace in these events. Indeed the

[16] Note that the derivation of this equation will be published at some point.

strange properties of these events has lead to purely geophysical explanations where it is proposed that Tunguska and other similar events are produced by some poorly understood coupling between tectonic and atmospheric process [51]. A fascinating possibility is that these strange events are simply the manifestations of the random collisions of the Earth with a mirror space body as described above.

Besides the purely scientific implications of this idea, there is also another ramification; if these strange events are due to mirror space bodies then it may be difficult to protect the Earth against the threat of impact with these objects (which may potentially pose an overall greater risk than space bodies composed of ordinary matter). An approaching space body made of (pure) mirror matter would not be detectable (only after they impact with the atmosphere would their effects be observable, but then it would probably be to late to do anything about them). However, mirror space bodies should contain some embedded ordinary matter, whether or not it is enough for the space body to be observable on its approach to Earth may be an important issue if we want to try to prevent potentially dangerous collisions.

Finally we finish with a few more related and hopefully interesting speculations. A popular theory for the origin of the moon is that it was formed when a large large asteroid (or small planet) impacted with the Earth during the early stages of the Earth's formation. However, one of the problems with this idea is that the chemical composition of the moon is too similar to the Earth's mantle. There should be a significant amount of extra-terrestrial material left over in the moon making the chemical composition of the moon more different to that of the Earth's mantle than it is known to be. However, if the colliding space body was made of mirror matter than this would alleviate this problem. First, a smaller body may be needed if it was made of mirror matter, especially if the bodies kinetic energy is released below the surface because this should make it easilier to liberate enough material to form the moon. Second, any mirror material left on the moon would eventually diffuse toward the moons center. In any case it would be undetectable and the composition of the moon would then appear similar to that of the Earth's mantle. It is also possible that such collisions could help explain the observed tilts in the axis of the Sun and planets, especially as mirror space bodies may orbit the Sun in planes other than the ecliptic.

6. Conclusion

It is a known fact that almost every plausible symmetry (such as rotational invariance, translational invariance *etc.*) are found to be symmetries of the particle interactions. Thus, it would be very strange if the fundamental interactions were not left–right symmetric. It is a very interesting observation that left–right symmetry requires the existence of a new form of matter called "mirror matter" otherwise there is nothing to balance the left-handed nature of the weak force. Even more interesting, is the remarkable evidence that mirror matter actually exists. The evidence ranges from studies of the most weakly interacting elementary particles (the neutrinos) to evidence that most of the mass in the Universe is invisible (*i.e.* dark matter). In fact seven fascinating puzzles have been identified, each suggesting the existence of mirror matter. While each individual puzzle is by itself not completely compelling, the totality of the evidence is impressive. Obviously if mirror matter does exist, it doesn't necessarily mean that all of the seven puzzles are manifestations of the mirror world (although they may be). Only further experiments/observations will provide the answer. Nevertheless, the question of the existence of the mirror world is probably one of the most interesting question in science at the moment, and it should (hopefully) be answered within the next 5 years.

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