THE MIRROR WORLD INTERPRETATION OF THE 1908 TUNGUSKA EVENT AND OTHER MORE RECENT EVENTS

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Mirror matter is predicted to exist if parity (*i.e.* left-right symmetry) is a symmetry of nature. Remarkably mirror matter is capable of simply explaining a large number of contemporary puzzles in astrophysics and particle physics including: Explanation of the MACHO gravitational microlensing events, the existence of close-in extrasolar gas giant planets, apparently 'isolated' planets, the solar, atmospheric and LSND neutrino anomalies, the orthopositronium lifetime anomaly and perhaps even gamma ray bursts. One fascinating possibility is that our solar system contains small mirror matter space bodies (asteroid or comet sized objects), which are too small to be revealed from their gravitational effects but nevertheless have explosive implications when they collide with the Earth. We examine the possibility that the 1908 Tunguska explosion in Siberia was the result of the collision of a mirror matter space body with the Earth. We point out that if this catastrophic event and many other similar smaller events are manifestations of the mirror world then these impact sites should be a good place to start digging for mirror matter. Mirror matter could potentially be extracted and purified using a centrifuge and have many useful industrial applications.

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One of the most natural candidates for a symmetry of nature is parity (*i.e.* left-right) symmetry. While it is an established experimental fact that parity symmetry appears broken by the interactions of the known elementary particles, this however does not exclude the possible existence of exact unbroken parity symmetry in nature. This is because parity (and also time reversal) can be exactly conserved if a set of mirror particles exist [1,2]. The idea is that for each ordinary particle, such as the photon, electron, proton and neutron, there is a corresponding mirror particle, of exactly the same mass as the ordinary particle. For example, the mirror proton and the ordinary proton have exactly the same mass. Furthermore the mirror proton is stable for the same reason that the ordinary proton is stable, and that is, the interactions of the mirror particles conserve a mirror baryon number. The mirror particles are not produced (significantly) 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 $\mathrm{G} \equiv \mathrm{SU}(3) \otimes \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{U}(1)_Y$ 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.* $\mathrm{G} \otimes \mathrm{G}$ (the ordinary particles are, of course, singlets under the mirror gauge symmetry) [2]. Parity is conserved because the mirror fermions experience $V + A$ mirror weak interactions and the ordinary fermions experience the usual $V - A$ weak interactions. Ordinary and mirror particles interact with each other predominantly by gravity only.

At the present time there is a large range of experimental evidence supporting the existence of mirror matter (for a review see Ref. [3]). Mirror matter is necessarily stable and dark and appears to provide a viable candidate for the inferred dark matter in the Universe [4] as well as having important implications for early Universe cosmology [4, 5]. Mirror dark matter also has self interactions just like ordinary matter which may allow it to escape the fate of collisionless cold dark matter candidates such as hypothetical neutralinos which now appear to be ruled out by the observations [6]. Moreover, mirror matter, like ordinary matter can form stars, planets and smaller bodies and there is interesting evidence for all these things. In particular mirror stars are a natural candidate [7] for the observed MACHO gravitational microlensing events [8]. Furthermore mirror planets would provide a simple explanation [9] for the existence of close-in extrasolar planets which has been puzzling astronomers since their unexpected discovery in 1995 [10]. There is also evidence that the 'dynamical mirror image' system of an ordinary planet orbiting a mirror star has also been observed but interpreted as an 'isolated' planet because light from the mirror star was not detected [11].

The significance of mirror matter for astrophysics and cosmology is clear, perhaps of equal importance though is the implications of mirror matter for particle physics. While ordinary and mirror matter interacts with each other predominantly by gravity, small non-gravitational interactions are actually possible. Due to constraints from gauge symmetry, renormalizability and parity symmetry it turns out that there are only 3 ways in which ordinary and mirror matter can interact with each other (besides gravity) [2,12]. This is via photon–mirror photon kinetic mixing, Higgs–mirror Higgs interactions and via ordinary neutrino–mirror neutrino mass mixing (if neutrinos have mass). While Higgs–mirror Higgs interactions will be tested if or when the Higgs particle is discovered, there is currently strong evidence for photon–mirror photon kinetic mixing and also ordinary neutrino–mirror neutrino mass mixing.

A simple consequence of the parity symmetry is that each of the ordinary neutrinos (ν) will oscillate maximally into its mirror partner (ν') [12–14]. This provides a very elegant explanation for the solar neutrino puzzle since the maximal $\nu_e \to \nu'_e$ oscillations imply an approximate 50% flux reduction for a large range of δm^2 which is in broad agreement with the solar neutrino data [15,16]. Moreover this solution predicted the approximate energy independent recoil electron energy spectrum observed by SuperKamiokande [17] as well as the $\sim$ 50% flux reduction found in the Gallium experiments [18]. In the case of the atmospheric neutrino anomaly the inferred 50% reduction of up-going ν_μ is also nicely explained by maximal $\nu_\mu \to \nu'_\mu$ oscillations [19]. If the solar and atmospheric neutrino anomalies are due to oscillations into mirror neutrinos then oscillations between generations can be governed by small mixing angles which seems theoretically most natural. This reasoning is supported by the LSND experiment which has provided strong evidence for small angle $\nu_e \to \nu_\mu$ oscillations [20].

It is true, though, that the solution to the neutrino physics anomalies implied by the mirror matter theory does not give a perfect fit to every neutrino experiment. However, this is probably a good thing, since it is unlikely that every experimental measurement is correct. In the case of solar neutrinos, the low Homestake result (1/3 *c.f.* 1/2 in the 6 other solar neutrino experiments) and also the recent SNO results [21] do not favour the simplest mirror matter solution. In addition the atmospheric data slightly prefer $\nu_\mu \to \nu_\tau$ to $\nu_\mu \to \nu'_\mu$ [22] (although the extent to which $\nu_\mu \to \nu'_\mu$ is disfavoured depends significantly on how the data is analysed [23]). Because these disfavouring results are only at the 1.5–3.3 sigma level (and are largely dominated by systematics) they do not provide a strong case against the mirror matter theory. Importantly things will eventually become clear as more accurate measurements are done. The forthcoming NC/CC SNO measurement should provide a solid result one way or the other.

Another important way that ordinary and mirror matter can interact with each other is via photon–mirror photon kinetic mixing. In field theory this is described by the interaction

$$\mathcal{L} = \frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} \,, \tag{1}$$

where $F^{\mu\nu}$ ($F'_{\mu\nu}$) is the field strength tensor for electromagnetism (mirror electromagnetism). This type of Lagrangian term is gauge invariant and renormalizable and can exist at tree level [2,24] or maybe induced radiatively in models without U(1) gauge symmetries (such as grand unified theories) [25–27]. One effect of ordinary photon–mirror photon kinetic mixing is to give the mirror charged particles a small electric charge [2, 25, 26]. That is, they couple to ordinary photons with electric charge εe.

The most important experimental constraint on photon–mirror photon kinetic mixing is that it modifies the properties of orthopositronium [26]. This effect arises due to radiative off-diagonal contributions to the orthopositronium, mirror orthopositronium mass matrix. This means that orthopositronium oscillates into its mirror partner. Decays of mirror orthopositronium are not detected experimentally which effectively increases the observed decay rate [26]. Because collisions of orthopositronium destroy the quantum coherence, this mirror world effect is most important for experiments which are designed such that the collision rate of the orthopositronium is low [28]. The only accurate experiment sensitive to the mirror world effect is the Ann Arbour vacuum cavity experiment [29]. This experiment obtained a decay rate of $\Gamma_{\mathrm{oPs}} = 7.0482 \pm 0.0016\ \mu\mathrm{s}^{-1}$. Normalizing this measured value with the recent theoretical value of $7.0399\ \mu\mathrm{s}^{-1}$ [30] gives

$$\frac{\Gamma_{\mathrm{oPs}}(\mathrm{exp})}{\Gamma_{\mathrm{oPs}}(\mathrm{theory})} = 1.0012 \pm 0.00023 \tag{2}$$

which is a five sigma discrepancy with theory. It suggests a value $\varepsilon \simeq 10^{-6}$ for the photon–mirror photon kinetic mixing [31]. Taken at face value this experiment is strong evidence for the existence of mirror matter and hence parity symmetry. It is ironic that the last time something important was discovered in high energy physics with a table top experiment was in 1957 where it was demonstrated that the ordinary particles by themselves appear to violate parity symmetry.

Of course this vacuum cavity experiment must be carefully checked by another experiment to make sure that mirror matter really exists. Actually this is quite easy to do. With the largest cavity used in the experiment of Ref. [29] the orthopositronium typically collided with the cavity walls 3 times before decaying. If the experiment was repeated with a larger cavity then the mirror world effect would be larger because the decohering effect of collisions would be reduced. For example if a cavity 3 times larger could be used (which means that the orthopositronium would typically collide with the walls just once before decaying) then the mirror world would predict an effect 3 times larger.

There are several important implications of photon–mirror photon kinetic mixing with the relatively large value of $\varepsilon \simeq 10^{-6}$ suggested by the orthopositronium vacuum experiment. These include:

- Exploding mirror stars (mirror supernova) will emit a burst of (ordinary) gamma rays. This would occur because at the temperatures ~ 10 MeV reached at the center of a typical supernova explosion the kinetic mixing will convert $e'^+e'^- \to e^+e^-$ which subsequently produces a relativistic fireball, which seems to qualitatively explain many of the features of the observed gamma ray bursts [32].

- Such a large value of $\varepsilon \approx 10^{-6}$ will lead to the light mirror particles $(e'^{\pm}, \gamma', \nu')$ being brought into equilibrium with the ordinary particles above $T = 1$ MeV in the early Universe [33]. While this is not a problem for the recent BOOMERANG, MAXIMA and DASI measurements [34] of the Cosmic Microwave Background [35], it does suggest that standard BBN needs modification. For example, there might exist a large electron neutrino asymmetry which can compensate for the faster expansion rate leading to acceptable values of the light element abundances [36]. Another possibility is that there might exist a large negative cosmological constant which will slow down the expansion rate at $T \sim 1$ MeV [14].

- Mirror stars can become visible if they have some embedded ordinary matter. This is because the ordinary matter is heated by the mirror matter though photon–mirror photon kinetic mixing. Maybe the recently observed halo white dwarfs [37] (which are controversial [38]) are really mirror stars [39] or even mirror white dwarfs. Because of their age they may have accreted enough ordinary matter to be observable.

Perhaps the most remarkable possibility though is that there is some significant amount of mirror matter in our solar system. We do not know enough about the formation of the solar system to be able to exclude the existence of a large number of Space Bodies (SB) made of mirror matter if they are small like comets and asteroids. The total mass of asteroids in the asteroid belt is estimated to be only about 0.05% of the mass of the Earth. A similar or even greater number of mirror bodies, perhaps orbiting in a different plane or even spherically distributed like the Oort cloud is a fascinating and potentially explosive possibility[1] if they collide with the Earth. The possibility that such collisions occur and may be responsible for the 1908 Siberian explosion (Tunguska event) has been speculated in Ref. [3]. The purpose of this paper is to study this possibility in detail and to point out the important ramifications of this idea which is that mirror matter should be present in the ground at the 'impact' sites and could be extracted as we will discuss.

[1] Large planetary sized bodies are also possible if they are in distant orbits [40].

If such small mirror bodies exist in our solar system 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 SB would simply pass through the Earth and nobody would know about it unless it was so heavy as to gravitationally affect the motion of the Earth. However, if there is photon–mirror photon kinetic mixing as suggested by the orthopositronium vacuum cavity experiment, then the mirror nuclei (with Z' mirror protons) will effectively have a small ordinary electric charge $\varepsilon Z' e$. This means that the nuclei of the mirror atoms of the SB will undergo Rutherford scattering off the nuclei of the atmospheric nitrogen and oxygen atoms. In addition ionizing interactions can occur which can ionize both the mirror atoms of the space body and also the atmospheric atoms. The net effect is that the kinetic energy of the SB is transformed into light and heat (both ordinary and mirror varieties) and a component is also converted to the atmosphere in the form of a shockwave, as the forward momentum of the SB is transferred to the air which passes through or near the SB.

What happens to the mirror matter SB as it plummets towards the Earth's surface depends on a number of factors such as its initial velocity, size, chemical composition and angle of trajectory. Of course, all these uncertainties occur for an ordinary matter SB too. Interestingly it turns out that for the value of the kinetic mixing suggested by the orthopositronium experiment, $\varepsilon \approx 10^{-6}$, the air resistence of a mirror SB in the atmosphere is roughly the same as an ordinary SB assuming the same trajectory, velocity mass, size and shape (and that it remains intact). This occurs because the air molecules will lose their relative forward momentum (with respect to the SB) within the SB itself because of the Rutherford scattering of the ordinary and mirror nuclei as we will show in a moment. (Of course, the atmospheric atoms still have random thermal motion.) This will lead to a drag force of roughly the same size as that on an ordinary matter SB, implying an energy loss rate of

$$\frac{dE}{dx} = C_d \rho_{\rm air} A \frac{v^2}{2}\,, \tag{3}$$

where $\rho_{\rm air}$ is the density of the air, v is the velocity of the SB and A is the cross sectional area. The drag coefficient, C_d is of order unity — its precise value depending on the shape of the body. We will take $C_d \sim 1$. Eq. (3) is a standard result and quite easy to derive: The pressure of the atmosphere on the surface of the body increases linearly with the velocity of the body. Also the number of atoms striking the surface will increase linearly with the air density and also velocity (since the volume that the body sweeps out in a given time t is just Avt). Eq. (3) implies that the bodies velocity decreases exponentially with distance (x),

$$v = v_i \mathrm{e}^{-x/D}\,, \tag{4}$$

where v_i is its initial velocity and

$$D = \frac{2R\rho_{\rm SB}}{C_d \bar{\rho}_{\rm air}} \sim 10 \left(\frac{R}{5\ \text{meters}}\right)\left(\frac{\rho_{\rm SB}}{1\ \text{g/cm}^3}\right)\ \text{km}\,. \tag{5}$$

In this equation, $\rho_{\rm SB}$ is the density of the SB and $R \equiv V/A$ is the 'size' of the body (V is its volume). Note that we have used $\bar{\rho}_{\rm air} \approx 10^{-3}$ g/cm^3 which is the air density at about 5 km altitude (the density at sea level is about twice this value) for a rough estimate of the mean density encountered as it travels through the atmosphere. The above calculation shows that the rate of energy loss of the SB in the atmosphere depends on its size and density. If we assume a density of $\rho_{\rm SB} \simeq 1$ g/cm^3 which is approximately valid for a mirror SB made of cometary material (such as mirror ices of water, methane and/or ammonia) then the body will lose most of its kinetic energy in the atmosphere provided that it is less than roughly 5 meters in diameter. Of course, things are complicated because the SB will undergo mass loss (ablation) and also potentially fragment into smaller pieces and of course, potentially melt and vaporize. Thus even a very large body (*e.g.* $R \sim 100$ meters as estimated for the Tunguska explosion) can lose its kinetic energy in the atmosphere if it fragments into small pieces.

An important difference between an ordinary and mirror SB is the rate and way in which it fragments, heats up and undergoes ablation because these properties depend very much on the interactions between the SB and the atmosphere. An ordinary matter SB undergoes huge pressure on its surface when it enters the atmosphere with cosmic velocity (~ 30 km/s) while in the case of a mirror matter body the effects of the pressure are distributed within the body to some extent, rather than just at the very surface. Let us now examine this in more detail.

Assume that the mirror matter SB is composed of atoms of mass $M_{A'}$ and the air is composed of atoms of mass M_A. The (mirror) electric charge in units of e of the (mirror) nuclei, which we roughly assume to be half neutrons and half protons, will be $Z = M_A/2M_P$ ($Z' = M_{A'}/2M_P$), where M_P is the proton mass. Let us assume that the trajectory of the SB is a straight line along the $\hat{z}$ axis of our co-ordinate system. In the rest frame of the SB, the change in forward momentum of each of the on-coming atmospheric atoms is then[2]

$$\frac{dP_z}{dt} = \Gamma_{\rm coll} M_A (v\cos\theta - v) = -2\Gamma_{\rm coll} M_A v \sin^2\frac{\theta}{2}\,, \tag{6}$$

[2] The following equation is valid provided that $M_{A'} \gg M_A$ but our conclusions will remain roughly the same for other cases of interest such as for $M_{A'} \sim M_A$.

where θ is the scattering angle in the rest frame of the SB and $\Gamma_{\rm coll}$ is the collision rate of the atmospheric atom with the mirror atoms in the SB. Of course, the collisions also generate transverse momentum (*i.e.* in the $\hat{x}$, $\hat{y}$ directions) which is reduced by thermalization effects as the atoms in the atmosphere interact with themselves. For the present calculation we are only interested in the relative net momentum between the SB and the atmosphere and we can neglect this transverse motion in a rough approximation (which means that we can replace v by v_z below). The collision rate $\Gamma_{\rm coll}$ is given in terms of the cross section, relative velocity and number density in the usual way:

$$\Gamma_{\rm coll} = \sigma v_z \left(\frac{\rho_{\rm SB}}{M_{A'}}\right) . \tag{7}$$

Thus Eq. (6) becomes

$$\frac{dP_z}{dt} = -2\left(\frac{M_A}{M_{A'}}\right)\int \frac{d\sigma}{d\Omega}\rho_{\rm SB} v_z^2 \sin^2\frac{\theta}{2}\, d\Omega\, . \tag{8}$$

There are various different processes which can contribute to the scattering cross section. For the velocities of interest, $v \lesssim 70$ km/s, the cross section is dominated by Rutherford scattering[3] of the mirror nuclei of effective electric charge $\varepsilon Z' e$ with the ordinary nuclei of electric charge Ze, modified for small angle scattering by the screening effects of the atomic electrons (at roughly the Bohr radius $r_0 \approx 10^{-8}$ cm). It is given by (see *e.g.* [42])[4]:

$$\frac{d\sigma}{d\Omega} = \frac{4M_A^2\varepsilon^2 e^4 Z^2 Z'^2}{(4M_A^2 v_z^2 \sin^2\frac{\theta}{2} + \frac{1}{r_0^2})^2}\, . \tag{9}$$

Thus we obtain from Eq. (8) and Eq. (9) the following differential equation for the distance traveled by each atmospheric atom (z) within the SB:

$$\frac{dP_z}{dt} = M_A\ v_z\frac{dv_z}{dz} \sim Z^2 Z'^2 \rho_{\rm SB}\frac{\varepsilon^2 e^4 4\pi}{M_{A'}M_A v_z^2}\log_e\left(\frac{1}{M_A v_z r_0}\right) , \tag{10}$$

which is valid for $M_A v r_0 \gg 1$. For $M_A \approx 15 M_P$, $M_A v r_0 \approx 700(v/30$ km/s$)$ which means that the above equation is approximately valid for the velocities of interest (the initial velocity, v_i, of a SB is typically between 15 and 60 km/s). Solving the above differential equation (neglecting the log factor which is of order 1) we find that the relative motion between the air molecules

[3] Although the cross section is dominated by Rutherford scattering, ionizing collisions may also be important for generating light and perhaps may also allow the body to build up electric charge within [41].

[4] We use standard particle physics units $h/(2\pi) = c = 1$ unless otherwise stated.

and SB is lost (upto random thermal motion) after traveling a distance within the SB of

$$z \sim \frac{v^4 M_A^2 M_{A'}}{16\pi Z^2 Z'^2 \rho_{\rm SB} \varepsilon^2 e^4} \sim \left(\frac{10^{-6}}{\varepsilon}\right)^2 \left(\frac{v}{30 \text{ km/s}}\right)^4 \text{ centimeters}\,, \qquad (11)$$

where we assumed $\rho_{\rm SB} \approx 1$ g/cm^3 and $M_A \approx M_{A'} \approx 15 M_P$ (with $Z \approx Z' \approx 7$). For $\varepsilon = 10^{-6}$, Eq. (11) indicates that the atmospheric atoms lose essentially all of their relative momentum (of course, they still have thermal motion) after penetrating a distance of the order of a few centimeters into the SB. (This distance may be somewhat greater for a body made of a heavy element such as mirror iron.) If the SB remains intact then the above result implies that the air resistence of the mirror SB through the atmosphere is roughly the same as that of an ordinary matter SB, as we already assumed earlier and have now proved. This *does not* mean that only the outer regions of the mirror SB will be heated by the atmosphere. The atmospheric atoms still have rapid thermal motion which will penetrate deep into the mirror SB. This is of course completely unlike a SB made of ordinary matter which remains cool inside. This 'internal heating' of the mirror SB should make it easier for the body to fragment and/or possibly build up enough internal pressure to explode. However, because the huge pressure from the atmosphere is dissipated over some distance within the body rather than just at its surface, the rate of ablation of a mirror SB may be significantly less than that of an ordinary SB.

Incidentally, if $\varepsilon \lesssim 10^{-8}$ instead of the value 10^{-6} indicated by the orthopositronium vacuum cavity experiment, a small or moderate sized SB would not lose significant energy in the atmosphere because the atmospheric atoms would pass through the body without losing much of their relative momentum. In this case the SB would release most of its energy underground in the Earth's crust. The distance over which this would occur would simply be given roughly by Eq. (11) with the replacement $\rho_{\rm SB} \to \rho_{\rm E}$ ($\rho_{\rm E}$ is the density of the Earth) and $M_A \leftrightarrow M_{A'}$, which is

$$L \sim \frac{v_i^4 M_{A'}^2 M_A}{16\pi \rho_{\rm E} Z^2 Z'^2 \varepsilon^2 e^4} \sim \left(\frac{v_i}{30 \text{ km/s}}\right)^4 \left(\frac{10^{-9}}{\varepsilon}\right)^2 \text{ km}, \qquad (12)$$

which was advertized earlier in Ref. [3].

Returning to the most interesting case of large photon–mirror photon kinetic mixing, $\varepsilon \simeq 10^{-6}$ which is indicated by the orthopositronium experiment, our earlier calculation suggests that most of the kinetic energy of a mirror matter SB is released in the atmosphere like an ordinary matter SB if it is not too big ($\lesssim 5$ meters) or fragments into small objects. It seems to be an interesting candidate to explain the 1908 Tunguska explosion (as well as smaller similar events as we will discuss in a moment). The Tunguska explosion toppled approximately 2 100 square kilometers of trees in a radial pattern (*i.e.* like spokes on a wheel) with an atmospheric release of energy estimated to be the TNT equivalent of roughly 1000 atomic bombs [43]. There was also evidence that the inner 300 square kilometers of trees was burned from above. The broad features of the event suggest a huge explosion in the atmosphere at an altitude of between about 2.5 and 9 km which produced a downward going spherical shockwave [43]. The spherical shockwave toppled the trees in the radial pattern and the heat from the explosion caused the flash burn of the trees [43]. An interesting feature of this event is the lack of any extraterrestrial fragments or any (ordinary) crater(s). The estimated mass of the SB is of the order of 100 thousand tons [43]. That is no typo. It is a remarkable result that such a large amount of extraterrestrial material apparently vanished without leaving behind significant remnants. Over the last 75 years about 35 scientific expeditions to the Tunguska site have been made with many types of search techniques, but all coming back empty handed. There have also been searches for microparticles in tree resin with some success [44]. However, their tiny abundance is hardly consistent with what might have been expected. It seems therefore to be a real possibility that the Tunguska event was due to a mirror matter SB which would not leave any ordinary fragments (the observed microparticles, if there are indeed of extraterrestrial origin, may simply be due to a small proportion of ordinary matter accreted within the mirror matter SB). Furthermore, the internal heating of the mirror SB by the interactions of the atmospheric atoms within the SB may actually cause the required atmospheric explosion.

It is also interesting to note that there is evidence that smaller 'Tunguska-like' events are actually quite common, occurring on a yearly basis. Such events have been catalogued by Ol'khovatov [45] with the most recent such event occurring only a few months ago in Jordan [46]. There are many events (see *e.g.* Ref. [46, 47]) where low altitude 'fireballs' are observed, yet such fireballs (if they are due to an ordinary matter SB) should originate from huge and enormously bright fireballs higher up in the atmosphere because of ablation and fragmentation. These bright parents of low altitude fireballs are inexplicably not observed. Even more remarkable is that these 'fireballs' have been observed in some cases to actually hit the ground (we will discuss an explicit example of this in a moment), yet no meteorite fragments were recovered. The strange properties of these events has lead to purely geophysical explanations. For example, it has been proposed that they are due to some poorly understood coupling between tectonic and atmospheric process rather than to some type of SB [45]. Mirror matter represents an exciting and fun alternative possibility which can be tested in a number of ways as we will now briefly discuss.

First, it requires large photon–mirror photon kinetic mixing of the order given by the orthopositronium experiment for the mirror SB to release its energy in the atmosphere. Thus, we could simply repeat the orthopositronium experiment to make sure that mirror matter exists with the required kinetic mixing. More work could be done in trying to understand the detailed properties of mirror matter space bodies interacting with the Earth's atmosphere which might allow the idea to be more rigorously compared with observations. For example, the 1997 Greenland event was observed with satellites and a ground based video camera [48]. This event has been estimated to be due to a 36,000 Kg SB which fragmented and exploded over Greenland. No fragments or even meteoritic dust in the snow was found by search teams [48]. The study [48] also found that the SB had an anomalous ablation coefficient [48] which might be something which could be used to possibly test the mirror matter hypothesis for these space bodies.

Perhaps the most spectacular way to test the idea though is to actually find it! Mirror matter could be searched for in the ground at the various impact sites. Any mirror matter fragments may have melted when they hit the ground and reformed becoming mixed with ordinary matter at some distance underground. The small effective ordinary electric charges of the mirror electrons (εe) which is given to them by the photon–mirror photon kinetic mixing should easily lead to enough electrostatic repulsion (which is linear in ε) to resist gravity, which means that the mirror matter will eventually stop (if it solidifies). There may be some amount close to the surface which could potentially be extracted and purified. Importantly, many of these sites are very localized and very accessible. For example, in the recent Tunguska-like event which occurred in Jordan (about 50 kilometers from the capital Amman) only a few months ago [46] the fireball was observed (by a crowd of about 100 people in a funeral procession) to break up into two pieces and observed to actually hit the ground! The two sites where the 'objects' landed featured a half burnt tree and a half burnt rock (see Ref. [46] for the remarkable pictures) but no ordinary crater and no ordinary matter fragments[5]. One could take samples of earth below the burnt tree (or the parts of the burnt tree itself) and try to extract mirror atoms. This might be possible by taking samples and putting them into a centrifuge which should allow the mirror matter to be separated from the ordinary matter (or at least greatly purified). It would be a very exciting experiment and lots of fun too!

Finally, mirror matter should have all sorts of useful industrial applications. Of course, it is premature to speculate too much along these lines

[5] Potentially a mirror matter SB could leave a type of impact crater depending on the chemical composition of the SB and also on the nature of the Earth's surface at the impact site.

until it is actually discovered, but the point is that its possible existence is not merely of interest to people who want to understand the fundamental laws of nature or find out what the Universe is made of. Unlike Higgs particles or top quarks it may actually be a very useful new material with all sorts of practical applications. This provides another important motivation to search for it, either by repeating the orthopositronium experiment in vacuum or by digging it out of the ground. Of course, I love Higgs particles and top quarks too but it is also important to remember that pure research in particle and astrophysics can sometimes lead to discoveries with widespread implications for society, in addition to the intrinsic merits and long term importance of such pure science itself.

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