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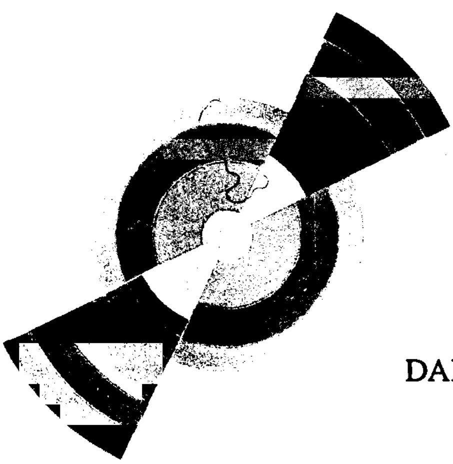

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G. Chardin

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International Workshop on Antimatter Gravity and Antihydrogen Spectroscopy, Molise, Italie, May 19-25, 1996

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MOTIVATIONS FOR ANTIGRAVITY IN GENERAL RELATIVITY

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We present arguments showing that it is natural to interpret the negative mass part of the Kerr solution as representing the geometry experienced by antimatter. The C, P and T discrete transformations are considered for this geometry. The C and T properties of the proposed identification are found to be in agreement with the usual representation of antimatter. In addition, we conjecture a property of perfect stigmatism through Kerr wormholes which allows General Relativity to mimic antigravity. Kerr wormholes would then act as "supermirrors" reversing the C, P and T images of an object seen through it. This interpretation is subject to several experimental tests and able to provide an explanation, without any free parameter, of the "CP"-violation observed in the neutral kaon system.

1. Introduction

Eight years before the discovery of CP violation, Morrison [1] considered the possibility that antimatter had a different weight that matter. I want here to reconsider this question. In particular, could it be that antimatter "antigravitates", i.e. that antimatter would be repelled rather than attracted by ordinary matter ? More precisely, could it be that Einstein's gravity itself predicts antigravity for antimatter ? For most of physicists, the answer to these two questions is obvious : the Equivalence Principle (for given initial conditions, neglecting spin effects, all bodies follow the same trajectories) is so central to the theory of General Relativity that it seems impossible that gravitation can distinguish and tell us anything specific about the weight of antimatter. However, as we shall see in the following, there are fairly good reasons to believe that General Relativity has found a way to defeat once more our intuition.

2. Phenomenological approach: antigravity to mimic Hawking radiation

The interest of the author for this curious question started approximately ten years ago when he was trying to prove that it was impossible that matter and antimatter had different weights without violating the stability of the vacuum (and the Second Law of Thermodynamics). The argument was the following : suppose there is an enormous difference between the force exerted on matter and antimatter in a gravitational field. If the difference becomes really enormous, we will end up by breaking the vacuum. As everybody knows, the vacuum can be considered to be composed of virtual particle and antiparticle pairs, and if some field differentiates between matter and antimatter, it will eventually become advantageous for the vacuum to create a particle-antiparticle pair instead of the empty vacuum.

We *do* observe such a disruption of the vacuum in the case of very large electric fields, and this is the Klein "paradox" (see e.g. [2]). By creating for a short moment a nucleus with more than approximately 140 protons (a little bit more than $1/\alpha_{em}$, protons, where α_{em} is the e.m. coupling constant), an unstable nucleus which can be created for a very short moment by the collision of two lighter nuclei, the electric field of the nucleus is so high and the electrons are so strongly attracted by the protons in the nuclei that it becomes advantageous to disrupt the vacuum. An electron-positron pair is produced and the electron hurls down towards the nucleus to reduce its charge while the positron is violently repelled by the remaining positive charge. Of course, it is out of question that such a violent difference between matter and antimatter could occur in the gravitational field of the Earth. But, as soon as the weight of matter and antimatter are just a little bit different, unlike the case of the electric field where nothing happens when the central charge of the nucleus falls below approximately $1/\alpha_{em}$, the vacuum starts to radiate to some extent. This instability of the vacuum, or so it seemed, was enough to exclude that antimatter could have a different gravitational weight that matter.

For most of today's physicists, just like at the time of Dirac, the instability of the vacuum is unacceptable. But, after a moment of reflexion, we have to face the following possibility. Suppose the vacuum instability is too weak to be noticed. As an example, suppose that the mass of the Earth is in fact concentrated in its centre as a singular point mass, i.e. a black hole. Classically, by Birkhoff's theorem, from the spherical symmetry of the problem, there is absolutely no way to distinguish the gravitational field created by a black hole with the mass of the Earth from the gravitational field of the real Earth with its decent and relatively uniform density. But quantum mechanically, there *is* a way to distinguish between the two situations: suppose for a moment that there really is a black hole at the centre of the Earth. Almost all physicists admit that some radiation will be emitted by the black hole through the Hawking mechanism [3]. But even if all the mass of the Earth was concentrated in this hypothetical central black hole, the radiation emitted by this evaporation process, effectively equivalent to an instability of the vacuum, would be so small

$$4\pi r_g^2 \sigma T_H^4 = 4\pi \times \left(\frac{2GM}{c^2}\right)^2 \times \sigma\left(\frac{\hbar c^3}{8\pi GMk_B}\right)^4 \approx 10^{-17}\, W$$

billions of time smaller than the power emitted by a single human body, that it would be totally out of question to experimentally detect it (in the above formula, r_g is the gravitational radius, M is the mass of the Earth, σ the Stefan constant, T_H is the Hawking temperature and k_B is the Boltzmann constant). In effect, we are faced here with a situation where a quantum physicist must agree that the vacuum would be unstable but at such a low level as to be undetectable.

After realizing that the instability argument should address the Hawking mechanism, we have then to reformulate the question in the following manner. Since Hawking radiation must be faced, what difference of gravitational weight between matter and antimatter would then be needed to mimic the accepted vacuum instability achieved in the Hawking process, where the black hole behaves as a grey body with temperature

$$\frac{\hbar g}{2\pi c}$$

and where g is the surface gravity ?

The answer is extremely surprising : we need antigravity. In other words, if we are ready to accept the level of vacuum instability experienced in the Hawking evaporation process, then, when antimatter antigravitates, the experimental consequences appear no more drastic than this already accepted instability.

Two simple arguments may allow to justify this statement: firstly, consider two Rindler wedges [4] accelerating one toward the left and the other towards the right each with an acceleration of magnitude $|g|$ relative to the background Minkowski spacetime. Both Rindler wedges share the same photons by definition; in addition, observers on each Rindler wedge will have an acceleration $2g$ relative to the other Rindler wedge and will measure a non-zero Unruh temperature [5] equal to

$$\frac{\hbar g}{2\pi c}$$

In the case of the Earth, this temperature is of the order 10^{-19} K, completely unobservable. Therefore, if we make the hypothesis that the consequences of vacuum instability will be of the same order in the case of antigravity as the corresponding problem in flat spacetime of the two Rindler wedges accelerating with respect to one another with an acceleration $2g$, we can see that the temperature measured by an observer on any of the two Rindler wedges is just the same expression as for the Hawking radiation.

A crude estimate of the typical energy of the photons which would be radiated by the vacuum in curved spacetime provides a similar answer. From the Heisenberg inequalities, a virtual creation-annihilation process involving a particle of mass m will probe spacetime over a length scale

$$\frac{\hbar}{\Delta mc}$$

where m is the mass of the propagated particle. Assuming antigravity, the typical energy of a photon which will be produced by the gravitational field is then:

$$\Delta E \approx mg\Delta z \approx mg\frac{\hbar}{mc} \approx \frac{\hbar g}{c}$$

Again, we find the approximate expression of the Unruh and Hawking temperature.

3. Phenomenological approach II : antigravity to mimic "CP"-violation in the kaon system

Of course, there is another well-known system where a very small difference in the gravitational behaviour of matter and antimatter would lead to observable consequences. The neutral kaon system has long been known to be this extremely sensitive system and has been used to impose the best existing constraints on the difference in gravitational behaviour between matter and antimatter ? In a celebrated paper [6], in 1961, Myron Good used the nonobservation, at that time, of anomalous vacuum regeneration to exclude a difference of gravitational behaviour between matter and antimatter in the neutral kaon system. It is this system, on the other hand, which exhibits the only known violation of the CP, or matter-antimatter, symmetry. In 1961, however, CP violation had not yet been discovered by Christenson et al. [7], as this profoundly surprising experimental result would have to await for three years to be discovered. And yet another ten years would be needed before the vacuum instability in the presence of a gravitational field evidenced by Hawking radiation [3] had to be faced. Therefore, it is not surprising that Good, disregarding the possibility that CP violation might be indeed violated, had formulated the question in a much more conservative way that we are led to consider here. Had it been known by Good at the time when he was building his argument that CP violation existed, and that the "vacuum instability" of the Hawking process was allowed by the laws of Nature, the answer could have been profoundly different because the question would have been asked in the more natural way : what kind of antigravity is needed to mimic and explain the extremely small and otherwise not observed CP violation ?

Let us come back for a moment to Good's argument. I have already noted elsewhere [8,9], as some other authors, that Good's argument relies on the assumption that an absolute gravitational potential is observable. Of course, as noted also by Nieto and Goldman [10,11], there is not a single example in physics where the value of a potential is observable. Only potential differences are observable, and not the potential themselves. Similarly, when CP-violation was discovered, Bell and Perring [12] and Bernstein, Cabibbo and Lee [13] supposed that the inertial mass of an antiparticle was depending on the potential. This is equivalent to a violation (a very strong violation) of CPT. Therefore, it is much more natural and satisfying to take as a starting hypothesis that the inertial mass of a particle and its antiparticle are always equal, irrespectively of the value of an otherwise unobservable potential. With this hypothesis, we can then ask what is the strength of the field (really just like an electric field) needed to mimic CP violation in the neutral kaon system. The answer to this question is again that antigravity is needed to explain CP violation. Indeed, the kaon has a rest energy of $\approx$500 MeV, so that its size, estimated from the negative kaon form factor [14], is ≈ 0.5 fm. The separation induced by antigravity between the K° and $\overline{K^{\circ}}$ components during the mixing time $\pi\hbar / \Delta mc^{2}$ of the weak interactions is

$$\Delta g\left(\frac{\pi\hbar}{\Delta mc^{2}}\right)^{2}$$

where Δg is the relative acceleration between the K° and $\overline{K^{\circ}}$. This quantity is close to $\varepsilon \times$(kaon size). *In other words, the time needed for antigravity to generate the amount of regeneration observed in CP violation is just equal to the mixing time imposed by weak interactions.* This provides an expression for ε :

$\varepsilon \approx \dfrac{\hbar m_{K} g}{\Delta m^{2} c^{3}} \times O(1)$, where the $O(1)$ factor takes into account the fact that the K° is made of a quark and an antiquark ($s\bar{d}$ or $\bar{s}d$).

These two remarkable coincidences, troubling as they are, are probably not sufficient to shake the confidence of the physicist in the usual expression of the Equivalence Principle which appears to be embedded so innerly in General

Relativity. It may seem hopeless in particular to respect the metric structure of General Relativity and yet to have a different behaviour in a gravitational field for a particle and an antiparticle. Let us show that this overconfidence is misplaced and that General Relativity probably manages, ironically, to mimic antigravity in a surprising but elegant way.

4. Negative mass and the Kerr geometry in General Relativity

It is often said that tensor gravity cannot accommodate repulsive gravity (see e.g. [11,15]). This view is mistaken and relies on a hidden and crucial assumption. In fact, as everybody knows (or should know), there are many examples, and some of them extensively studied, of repulsive gravity in General Relativity : inflation, cosmological constants, wormholes and, generically, the Kerr [16] and Kerr-Newman [17] geometries all provide examples of repulsive gravity. It is then clear that there is only a contradiction between General Relativity and repulsive gravity if we insist that the averaged null energy condition (ANEC) [18] is respected. If, on the other hand, we accept negative mass and negative energy densities as physically acceptable, then repulsive gravity appears immediately. It should be noted, in particular, that the most stringent experimental constraints which are usually considered to rule out antigravity [15] are only valid when negative energy densities are excluded.

At the quantum level, on the other hand, negative energy densities appear unavoidable and the consistency of the theory requires that they be present at some level. In particular, Morris, Thorne and Yurtsever [19,20] have noted that the Casimir vacuum between parallel conducting plates provides a physical example of negative energy densities [21]. Similarly, Hawking radiation [3], allowing a decrease of the horizon area of a black hole, implies a negative average energy density. The consistency of quantum mechanics then requires that we accept as physical these negative mass solutions.

Now, every undergraduate student, if asked in a persuasive way, would probably guess that negative masses are associated with antimatter. Curiously, it is difficult to find in the litterature a single association between negative mass in General Relativity and antimatter. Instead, Simon notes, writing about these solutions [22] "Here, negative mass-energy does not mean antimatter, but matter that will gravitationally repel other matter, and thus excludes all known types of classical matter". However, over the last ten years, the extensive study of wormholes and of the Kerr solution have provided more and more indications that this association between negative mass and antimatter was in fact natural or, following Wheeler's expression, "obvious and incredible".

As noted above and as first shown by Carter in the late sixties [23,24], this notion of repulsive gravity is present in basically all the exact solutions of General Relativity, namely the Kerr and Kerr-Newman solutions. Ironically, the Schwarzschild solution is probably the only known exact solution which does not exhibit naturally maximal extensions with both types of regions with attractive and repulsive gravity (although Carter [23] has shown that such an extension can be made). The exceptional character of the Schwarzschild solution had been noted by Israel [25] who showed that this geometry is the only solution which is bounded by a simple nonsingular Killing horizon. In the

Schwarzschild solution, in order to be able to explore the repulsive part of the geometry, a test particle would need an infinite energy to cross the Kerr wormhole connecting the two regions which degenerates in the Schwarzschild case in the $r = 0$ singularity. Therefore, in this solution, the attractive and repulsive regions are effectively disconnected and the repulsive part of the solution is therefore usually completely ignored. Such is not the case for the Kerr and Kerr-Newman geometries. The two m and $-m$ regions, as shown by Carter, are connected by a Kerr wormhole (Thorne uses this denomination of Kerr wormhole for the tunnel connecting the positive and negative mass regions of the Kerr geometry although this term is usually restricted to the more complex solutions first studied by Morris, Thorne and Yurtsever [19,20]).

What are the reasons which are usually invoked for considering this solution as non-physical ? The answer to this question lies, firstly, in the instability of the solution and, secondly, in the violation of causality which appears to be allowed by traveling in the negative mass region of the Kerr solution. In other words, it seems, at least at first sight, that it is possible to go back in the past by using this part of the solution. For this reason, clamorous claims [26] have been made regarding time travel over the past ten years, following the study by Thorne and others of the surprising properties of these negative energy solutions. It should be clear that it is out of question in our opinion that we can travel backward in time in order, for example, to assassinate our parents. As we shall see, Nature seems very well protected against such paradoxes and manages apparently quite well to accommodate these negative energy solutions.

5. The C, P and T discrete symmetries

In retrospect, it would seem that the two problems linked with the negative mass regions of the Kerr solutions, instability and time travel, would be sufficient arguments to reconsider the possibility that negative masses, very similarly to the Dirac solutions which suffered from the same problems, would represent antimatter.

Let us look more precisely in this direction by considering each of the three discrete transformations C, P and T, in order to establish whether or not this surprising interpretation fits the properties expected from antimatter.

Let us first look at the C transformation. For this, it is obviously adapted to use the Kerr-Newman solution [17] of a charged rotating black hole. Following Carter [23], and disregarding for the moment the instability of the negative mass region, let us launch a charged test particle, e.g. an electron, along the axis of a Kerr-Newman black hole with sufficient energy to penetrate the negative mass region. Let us assume that in the positive mass part of the Kerr-Newman solution, the central body is endowed with mass m, charge e and angular momentum a, using the notations of Carter [24]. If our interpretation that the negative mass part of the Kerr solution represents the geometry experienced by an antiparticle is correct, our electron should be seen by the central body as a positron in the negative mass region. Equivalently, our electron should measure for the central body a charge $-e$, opposite to the charge seen in the positive mass region, when exploring the negative mass part of the solution. For example, if the electron interprets the massive body as a collection of electrons in the attractive region of the solution, it should see it as the same number of *positrons* when travelling in the repulsive part if our interpretation of antimatter is correct. As shown by Carter [24], this is indeed the case, a strong indication that our identification is correct.

This property can be simply evidenced by considering the Kerr-Newman metric expressed in advanced Eddington-Finkelstein coordinates

$$ds^2 = \left(r^2 + a^2\cos^2\theta\right)d\theta^2 - 2a \times \sin^2\theta dr d\varphi + 2 dr du +$$
$$\left[\left(r^2 + a^2\right)^2 - \left(r^2 - 2mr + a^2 + e^2\right)a^2\sin^2\theta\right]\sin^2\theta d\varphi^2 / \left(r^2 + a^2\cos^2\theta\right)$$
$$-2a\left(2mr - e^2\right)\sin^2\theta d\varphi du / \left(r^2 + a^2\cos^2\theta\right) - \left(1 - \frac{\left(2mr - e^2\right)}{\left(r^2 + a^2\cos^2\theta\right)}\right)du^2$$

and the associated electromagnetic tensor exterior form

$$F = \frac{2e}{\left(r^2 + a^2\cos^2\theta\right)^2}\begin{bmatrix}\left(r^2 + a^2\cos^2\theta\right)dr \wedge du - 2a^2 r\cos\theta\sin\theta d\theta \wedge du \\ -a\sin^2\theta\left(r^2 - a^2\cos^2\theta\right)dr \wedge d\varphi + 2ar\left(r^2 + a^2\right)\cos\theta\sin\theta d\theta \wedge d\varphi\end{bmatrix}$$

where a is the specific angular momentum, e is the electric charge and m is the mass. From the above expression, it can be seen immediately that in the negative mass region ($r < 0$), the electric charge of the central object can be reinterpreted as being equal to $-e$ (and its gravitational mass $-m$).

Consider now the T transformation. Although the CPT theorem has not generally been demonstrated on curved spacetime, if CPT is, at least locally, a good symmetry, antimatter is basically matter traveling backward in time, since CP is the matter-antimatter transformation and T is the time-reversal operator. If our interpretation is correct, antimatter is *exactly* matter traveling backward in time and the apparent CP-violation in the neutral kaon system is just due to the matter-antimatter asymmetry of the environment. Near an anti-Earth, the "CP"-violating decay of the neutral kaon would be described in the very same way by an anti-physicist and it would be impossible to define an experiment allowing unambiguously to define antimatter relative to matter, whereas such a definition is possible in the presence of CP-violation [27]. In addition, the fact that a particle can follow a Closed Timelike Curve (CTC) when it is allowed to travel in the negative mass part of the solution is an indication that when it travels in this region, the particle is nothing else, with respect to the central mass, that an antiparticle, i.e. a particle traveling backward in time, following the Wheeler-Feynman representation of an antiparticle. The possibility of non-trivial CTCs between *any two points* of the Kerr geometry when the condition $m^2 < a^2 + e^2$ is verified has been noted by Carter [24].

To look more precisely at the T transformation, we need to understand how the two regions of negative and positive mass might be able to communicate. One of the least satisfying aspects of the interpretation ascribing the negative mass part of the Kerr geometry to antimatter (note that here, unlike in the conventional interpretation, antimatter is defined not absolutely but relative to the central body) is the fact that it seems difficult to see how a particle can determine its position in spacetime relative to an antiparticle. In particular, when the negative mass part of the Kerr geometry is discussed, the expression "another universe" is commonly employed since the negative and positive mass regions of the Kerr geometry, although with the same topology, appear as two distinct regions of spacetime. How is it then possible to make a natural identification between the negative and the positive mass parts of the Kerr geometry ? In other words, how can a particle determine when it is at the same point as an antiparticle if they travel in two different universes ?

In order to answer this question, let us try to use an operational approach. Suppose we turn on a light bulb at some point r, t, θ, φ on the positive mass region of the Kerr geometry. If the light rays emitted by the light bulb converge perfectly at some other point (i.e. there is perfect stigmatism between the emission point and this second point), an observer will have the impression that the light bulb is also present at the second point. Note that a very similar property is respected by the wormholes studied by Thorne et al. : for example, for a wormhole of negligible length connecting a place on the surface of the Earth to a place on the surface of Mars, an object crossing the wormhole is seen both on the Earth and on Mars, i.e. there is a property of perfect stigmatism between the two mouths of the wormhole. Therefore, for any massless field emitted by the light bulb, there will be no observable difference between the presence of the light bulb itself and its image.

Coming back to the Kerr geometry, suppose now that this property of perfect stigmatism is verified and that the stigmatic point lies on the other side of the Kerr tunnel in the negative mass region. We will then have found a mechanism which allows to see the image through the Kerr wormhole of an object residing in a place where antigravity exists. Therefore, we will have the impression that the object is "really" in our positive mass region and yet antigravitating. In other words, we will have found a way for General Relativity to mimic antigravity. The simple geometrical structure of the Kerr geometry in 2 + 1 gravity [28] gives some confidence in our stigmatism conjecture.

6. Causality violations and instability

Why are we so reluctant then to consider the possibility that this negative mass part of the Kerr solutions might represent antimatter ?

Firstly, concerning the problem of causality violation, the discussion initiated by Echeverria, Klinkhammer and Thorne [29] shows that it is quite probable that Nature will perfectly manage to protect itself from the CTCs allowed by wormholes and the Kerr geometry. Strong arguments in this direction have been given by Friedman et al. [30,31] where these authors have shown that the Cauchy problem is well defined on a class of spacetimes with CTCs which then appear as relatively innocuous.

Secondly, there is of course the instability of the solution. But as our crude estimate of the instability of the solution showed, it is far from obvious that this instability, of the order of the Hawking effect, is not an argument in *favour* of our interpretation. Ironically, antigravity may re-establish the Equivalence Principle in a situation where the vast majority of the physicists had accepted its violation since conventional wisdom asserts that it *is* possible to determine whether you are on the surface of a neutron star and trying to resist to a gravitational field, or accelerating in an elevator in flat spacetime : just measure the temperature (in a very quiet environment...). If the temperature is zero, you lie on the surface of the neutron star. On the other hand, if the temperature is different from zero, you are in an elevator accelerating in flat spacetime.

Stated differently, since the discovery by Bekenstein and Hawking of the entropy and the thermal evaporation of black holes, vacuum instability for any massive structure must be faced at some level. It is therefore far from clear that the instability induced by the negative mass region of the Kerr geometry has more dramatic consequences than the Hawking radiation.

7. Experimental tests

Our antigravity hypothesis has several testable consequences (see also [8,9]). For example, since the ε parameter of CP violation in the kaon system appears to be proportional to g, it is tempting to try to measure this parameter in conditions where the intensity of the gravitational field is different from the conditions at the surface of the Earth. At the surface of the Moon, the CP-violating amplitude would be six times smaller than on the surface of the Earth, and the "CP"-violating decay rate 36 times smaller. Coming back to more realistic experiments, one might consider the possibility to measure the CP-violating ε parameter in various places on the Earth. However, the difference in amplitude of g at the surface of the Earth is too small to be measured in the neutral kaon system : the ellipsoidal shape of the Earth only accounts for half a percent in the variation of intensity of the gravitational field at maximum, between the equator and the pole. This results in an effect at most equal to the precision (at the 1 sigma level) of the Particle Data Group estimate of this parameter. In addition, all the particle physics facilities are approximately at the same latitude (approx. 45° north), thereby reducing the spread in the value of g to a negligible level.

Allen Mills [32] has suggested that a measurement of the ε parameter could be realized on board the space shuttle. The typical altitude of the space shuttle is 500 km and could possibly be increased to 1000 km. At the lowest altitude, the decrease on the "CP"-violating decay rate would be 14 %, and 25 % at the highest altitude. A possibility to actually realize this experiment would be to use a magnetic bottle of the type developed by Gerald Gabrielse [33] and Michael Holzscheiter [34] for LEAR experiments PS196 and PS200 respectively. These traps have been shown to capture and hold up to 10^6 antiprotons for several months under optimum vacuum conditions, and the latter experiment has demonstrated the capability of extracting antiprotons from the trap to external experiments [35]. Development of transportable versions of this system is in progress [36]. Antiprotons would then be slowly extracted from the trap and annihilated in an hydrogen target. As for the CP-LEAR experiment at CERN [37] which uses the same production mechanism of neutral kaons, the proportion of events which include a neutral kaon in the annihilation process is approximately 0.4 %. Measuring the ε parameter using only the charged pion decay and assuming a drift chamber detector of the type used at CP-LEAR [37] but with a 50 % geometrical efficiency, we can estimate that the annihilation of 10^{10} antiprotons, whose storage may possibly be achieved with proposed traps, would allow a 5 σ effect at the lowest altitude and approximately a 10 σ effect at the highest altitude. In an elliptical orbit, the variation of the ε parameter as a function of the altitude would be an unambiguous signature of the gravitational nature of the "CP"-violation in the neutral kaon system.

T-violating effects such as the existence of an electric dipole moment of the neutron are of course predicted to be zero in this interpretation.

8. Conclusions

We have shown that the interpretation, within conventional General Relativity, of the negative mass part of the Kerr metric as representing the metric experienced by antimatter (relative to the central massive body) fits rather nicely with the discrete symmetries C and T. Concerning the P symmetry, we have conjectured the property of perfect stigmatism between the negative mass and the positive mass part of the Kerr solution through the tunnel linking the two regions. By referring to the wormholes solutions extensively studied over the last few years, we have shown that this property of perfect stigmatism is indeed natural. If our conjecture is verified, then the Kerr geometry appears as a "super-mirror", acting not just through the P transformation, but also through the C and T transformations thereby allowing General Relativity to mimic antigravity. In this interpretation, antimatter is just matter observed through the Kerr wormhole and therefore C-, T- and, if our property of stigmatism is verified, P-reversed. The wormholes first studied by Thorne and collaborators appear as more complex objects which also exhibit this property of perfect stigmatism that we have conjectured for the Kerr geometry but which conserve the parity and time direction of the object seen through the wormhole.

Finally, this interpretation of the negative mass region of the Kerr geometry would provide an explanation, without any free parameter, of the CP violation observed in the neutral kaon system together with a simple expression for the ε parameter. The prediction that the ε'/ε parameter for the neutral kaon system must be zero together with the prediction of a very small value ($\approx 3\ 10^{-6}$) of the "CP"-violating amplitude for the B system allows experimental tests of our hypothesis. Measuring the weight of antiparticules and the CP-violating parameter for the neutral kaon system in the space shuttle represent more ambitious experiments which would provide totally unambiguous signatures of this interpretation.

Acknowledgments

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