Testing General Relativity with the Neutral Kaon System

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Abstract

The arguments favouring gravitation as the "Master Arrow of Time" are briefly reviewed and the possibility that CP violation observed in the neutral kaon system may be explained by a violation of the Equivalence Principle is discussed.

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Introduction

"Quid est tempus ? Si nemo a me quaerat, scio; si quaerenti explicare velim, nescio !"
ST. AUGUSTINE, *"Confessions"*, Book XI.

When asked about the origin about time-asymmetry, most physicists mumble a few (almost indistinct) words like "entropy" or "Boltzmann theorem". Surprisingly, a remarkably small number of high-energy physicists seem to be aware of the developments of the last twenty years about time-asymmetry. Most of these developments [Bek73, Haw75, Pen79, Zeh89] point in the direction of gravitation as the "Master Arrow of Time" and it is therefore extremely surprising to note that the only evidence for a microscopic time-asymmetry —the so-called CP violation in the neutral kaon system— is considered to be unrelated to the other "arrows of time". Indeed, the very existence of the neutral kaon system has been used, on the contrary, as a means to constrain the difference of gravitational interaction between matter and antimatter [Goo61, Ken90].

Every ten years or so [Gol67, Gal74, Dav74, Pen79, Zeh89], an attempt is made to gather in a unified context the various arrows of time which can be observed or conjectured in Nature —the decay of the K°-meson, quantum-mechanical observations, general entropy increase, retardation of radiation, psychological time, cosmological expansion and the black holes versus white holes puzzle. Retrospectively, it appears that the timing of the reviews on time-asymmetry was rather ironical : for example, "The Nature of Time" [Gol67] is based on a workshop held in May-June 1963, a few months before the experimental discovery of CP violation [Chr64]. Similarly, "The Physics of Time-Asymmetry" [Dav74] misses the findings of Bekenstein [Bek73] and Hawking [Haw75, 76] on the fundamental relation of entropy and the Second Law of Thermodynamics with gravitation by a few months.

Under the demoralizing influence of Kobayashi and Maskawa, the "explanation" of CP violation in the standard model has been essentially reduced to the counting of free parameters in a 3x3 unitary matrix, and most authors have considered the neutral kaon system as irrelevant to the question of time asymmetry, with a few notable exceptions. The reader who would like to further explore the subject of time-asymmetry should refer to [Gol67], [Gal74], [Dav74], [Pen79], [Lan82] and [Zeh89]. Although largely self-consistent, this paper can also be understood as complementary to [Cha90] and [Cha92].

Gravitation and the Master Arrow of Time

"We have reached a remarkable conclusion. The origin of all thermodynamic irreversibility in the real universe depends ultimately on gravitation. Any gravitating universe that can exist and contains more than one type of interacting material must be asymmetric in time, both globally in its motion, and locally in its thermodynamics."
P.C.W. DAVIES, *"The Physics of Time-Asymmetry"*, 1974

What are the arguments for insisting that Gravitation is at the origin of the Master Arrow of Time ? The first argument comes from the structure of the solutions of General Relativity : massive bodies dissipate their energy while collapsing and this dissipation will only end when the massive body will have completely evaporated. The example is well-known of the satellite which increases its speed when being dragged by the atmosphere —a consequence of the surprising "minus" sign in the expression of the virial theorem— and it was realized by Chandrasekar that sufficiently massive bodies will contract without limit, resulting in "black holes". Now, it may seem at first sight that we have found just the opposite of what we intended to demonstrate : the classical picture of a black hole provides us with an object where no dissipation is possible since even light is trapped in it. But it follows from the work of Bekenstein [Bek73], refined by Hawking [Haw74], that even black holes must evaporate by thermal emission —the so-called Hawking radiation— a process imposed by the consistency with quantum mechanics. The fate of very massive structures seems to be of little relevance to the future of most celestial bodies, but again quantum mechanics allows the tunneling, albeit incredibly slow, of any massive body into a black hole and its subsequent evaporation in thermal, structureless radiation. In this respect, gravitation has been known for twenty years to be linked with time-asymmetry, a relation exemplified by the generalized Second Law of Thermodynamics formulated by Bekenstein.

A second and more subtle argument is provided by the work of Penrose [Pen65] and Hawking [Haw67] : if we assume the validity of General Relativity, the existence of a past singularity in our universe is unavoidable and Penrose has conjectured through his "Weyl curvature hypothesis" [Pen79] that any past singularity —the Big Bang— is associated with a low gravitational entropy which Penrose associates with a vanishing Weyl curvature, whereas future singularities like black holes would be associated with a huge Weyl curvature and entropy. This brings us to an important comment concerning the CPT theorem : most theorists would not pay any attention to your pet theory if it violated CPT symmetry. But as should be well known, the possibility of demonstrating the CPT theorem depends on the topology of spacetime : the unavoidable existence of past singularities (assuming the validity of General Relativity) makes it very doubtful that the CPT theorem can be demonstrated without modification for gravitation. In other words, boundary conditions cannot be eliminated. This point can be expressed more dramatically using the following remark : the dimensionless quantities entering the quantization of electroweak and strong interactions are *local* quantities —the coupling constants; as is well known, no such local expression has been found in the case of gravitation (the theory is non renormalizable). Instead, the only dimensionless quantity is here a *non-local or global* quantity : entropy or information (the presence of the Boltzmann constant in the usual expression of entropy is irrelevant; its physical content is expressed in bits, and can be measured (at least in principle) through the reversible coupling of a black hole with a gas of photons contained in a reflecting box [Zur82]). It is then probable that in a most fundamental sense, the quantization of gravity has been expressed twenty years ago through the Bekenstein entropy relation : $S = M^2$.

Reexpressing the Good argument

"It is hard to believe that Nature is not, so to speak, 'trying to tell us something' through the results of this delicate and beautiful experiment, which has been confirmed several times."

R. PENROSE, in *"General Relativity, an Einstein Centenary Survey"*, 1979

In the following, we will be defending the provocative idea that CP violation as observed in the neutral kaon system can be entirely due to a violation of the Equivalence Principle. As a starting point, let us use Morrison's antigravity [Mor58], a gross violation of the equivalence principle where antimatter is assumed to "fall up", the total force on a static $e^+ e^-$ pair, e.g., being zero. Note that such a definition for antigravity cannot be valid for ultrarelativistic particles : a photon is its own antiparticle (if we disregard its polarisation) and is known [Pou60; Ves76] to follow the equivalence principle. We will address the question of the relativistic expression of antigravity when discussing the compatibility with the Second Law.

It is "well known" that antigravity violates the sacrosanct CPT symmetry, contradicts the results of the Eötvös-Dicke-Panov experiments, excludes the existence of the long-lived component in the neutral kaon system in the presence of the Earth gravitational field, violates energy conservation and implies vacuum instability. Except for the last one, these arguments have been reviewed critically by Nieto and Goldman [Nie91] and, although we disagree with the solutions proposed by these authors, we refer the reader to their recent review for a critical discussion of these impossibility arguments (see also [Cha90] and [Cha92]). Here, we will only insist on the Good argument and on the apparent violation of energy conservation.

In 1961, *three years before the first experimental observation of CP violation*, Good [Goo61] observed that antigravity would impose that the K_L, a linear combination of K° and $\overline{K^\circ}$, would regenerate a K_S component. Good estimated the phase shift which would develop between the K° and $\overline{K^\circ}$ components from the energy difference due to the gravitational potential ϕ_G; he supposed that the phase factor between the two components would oscillate as

$$\exp(2i\ m_K \phi_G\ t/\hbar).$$

Since the potential energy of a kaon in the Earth gravitational field is ≈0.4 eV, which is 10^5 larger than the energy splitting between the K_S and K_L eigenstates, Good concluded that antigravity was excluded. But, as Good himself had noticed, there is no obvious reason why one should use the Earth potential; why not use instead the Sun, or the Galactic potential which would give even more stringent limits on the difference of acceleration between matter and antimatter ?

In fact, gauge theories teach us that potential themselves are not observable, but only potential differences. Let us then try to restate the Good argument independently of absolute potentials. A kaon has a rest energy of ≈500 MeV, its size is then $\approx \hbar/m_K c \approx 0.4$ fm. Obviously, if there is a mechanism which separates the s quark from the $\bar{s}$ quark (and/or d from $\bar{d}$) by more than the size of the kaon during the mixing time $\Delta\tau$ introduced by weak interactions, which continuously transform $s \leftrightarrow \bar{s}$ (and $d \leftrightarrow \bar{d}$), $\Delta\tau \approx \pi\ (\hbar/\Delta mc^2)$, a large K_S amplitude (typically 0.5) will be regenerated. Assuming antigravity, let us estimate the time needed for the s quark to separate from the $\bar{s}$ to a distance that would induce a regeneration of the K_S component such as observed in CP violation. This time is given by the equation

$$gt^2 \approx \varepsilon \times (kaon\ \ size) = \varepsilon \times \hbar/m_K c. \qquad (1)$$

where ε is the CP violating parameter.

This gives numerically

$$t \approx 3\ 10^{-10}\ \text{s} \approx 1.7\ \hbar/\Delta mc^2$$

In other words, the time needed for antigravity to generate the amount of regeneration observed in CP violation is just about equal to the mixing time imposed by weak interactions. Expressed independently of absolute potentials, the Good argument, far from excluding the possibility of antigravity, provides an indication that CP violation may be explained by some kind of antigravity ! From equation (1), we are then led to the following approximate expression for the ε parameter

$$\varepsilon = O(1)\ \hbar m_K\, g\ /\ \Delta m^2 c^3 = O(1) \times 0.88\ 10^{-3} \qquad (2)$$

which is the only dimensionless quantity linear in the kaon mass which can be built from the above quantities. This expression has a simple physical interpretation : it means that the energy to lift a kaon by $\Delta z = \hbar/\Delta mc$ is of the order of $\varepsilon\ \Delta mc^2$. It is difficult to believe that Good himself would not have proposed the previous expression for ε if CP violation had been observed at the time when he devised his argument. For a different expression of the argument leading to equation (2), see also [Cha90]. Fischbach [Fis80] had also noted that the quantity $\hbar m_K\, g\ /\Delta m^2 c^3$ is of the order of the experimental value of ε.

Vacuum instability and black hole radiation

“The information thus solicited makes physics and comes in bits. The count of bits drowned in the dark night of a black hole displays itself as horizon area, expressed in the language of the Bekenstein number”.”

J.A. WHEELER, in *“Complexity, Entropy and the Physics of Information”*, 1990

As noted previously, a classical argument against Morrison's antigravity, devised by the author himself [Mor58], is that energy conservation must be violated by this process. But if, as we suggest, the behaviour of the neutral kaon system is linked to the failure of time invariance under (*continuous*) time translations (instead of the *discrete* symmetry usually considered), we may expect some problems with energy conservation : from Noether's theorem, a conserved quantity named energy can only be defined whenever invariance under time translations is respected. Any process defining an “arrow of time” may then forbid the construction of energy as a conserved quantity (instead, as we shall see, *entropy* will become the relevant quantity). Such an apparent violation of energy conservation is already present in the process of black-hole evaporation : while trying to find a static solution for a system including a black-hole Hawking [Haw74], to his surprise, discovered that no such solution existed; instead, the black hole appeared to behave like a grey body with a temperature $k_B T_{bh} = \hbar g/2\pi c$, where g is the surface gravity of the black hole and k_B is the Boltzmann constant. A similar example is provided by the Unruh effect [Unr76], related to the previous effect : a uniformly accelerated detector in vacuum measures a non zero temperature proportional to its acceleration, $k_B T_u = \hbar g/2\pi c$. Here also, it may seem at first sight that there is violation of energy conservation : a detector is excited *and* there is emission of photons.

The apparent violation of energy conservation by antigravity can be evidenced in the following way : if one had antigravity, the total force on an $e^+ e^-$ pair would be zero and it would be possible to carry adiabatically an $e^+ e^-$ pair at a higher altitude Δz at no cost. Annihilating the $e^+ e^-$ pair into two photons, we would propagate downwards the two photons to the lower altitude, and there recreate the $e^+ e^-$ pair. After the fall in the gravitational field, however, we know from the experiments of Pound and Rebka [Pou60] and Vessot and Levine [Ves76] that each of the two photons has gained an energy $mg\Delta z$.

It then seems that we have the possibility to realize a *cyclic* process resulting in the extraction of a photon from the gravitational field. Namely, an $e^+ e^-$ pair is annihilated at the altitude Δz, and the annihilation photons transported to the lower altitude where a pair is recreated with the emission of a photon of energy $2mg\Delta z$; the $e^+ e^-$ pair is then carried back, at zero energetic cost, at the altitude Δz. It then seems that we have obtained “something for nothing” and that we have realized the construction of a perpetual engine. Certainly, we should not expect to solve the energy crisis with such a process, but it appears that, even if there are no “real” particles present, the vacuum becomes unstable in the presence of a gravitational field. Let us find the typical energy of photons created in virtual creation-annihilation processes in the vacuum. From the Heisenberg inequalities, a virtual creation-annihilation process will probe spacetime over a length scale $\Delta z \approx \hbar/mc$, where m is the mass of the propagated particle. Assuming antigravity, the typical energy of a photon which can be extracted from the gravitational field is then: $\Delta E \approx m\, g\, \Delta z \approx \hbar g/c$. The associated wavelength is $\lambda \approx c^2/g$, approximately one light-year at the surface of the Earth, and is therefore almost unobservable. The attentive reader will have noticed, however, that a similar expression of a “vacuum temperature” enters the Bekenstein-Hawking radiation of black holes. *The vacuum instability induced by antigravity then appears very similar to the very effect which introduces the second law and time-asymmetry in the realm of general relativity*. If black-hole evaporation is acceptable, why should we reject a priori a similar effect induced by antigravity ?

The thermal character of the radiation in the case of antigravity can be qualitatively justified by the following remark : Boyer [Boy84] had noted that if one applied “naively” the equivalence principle, there was an irreducible lowest temperature attainable for any experiment at the surface of the Earth. Since an object at rest on the Earth does not follow its geodesic path and is therefore accelerated, its temperature would be given by the Unruh expression $k_B T_u = \hbar g/2\pi c$. At first glance, this seems to be a disaster since no really static situation would exist : not only black-holes, but *any* massive object would evaporate. The conventional viewpoint is that such an evaporation is impossible since energy must be conserved [Gri87] but the argument is circular since it presupposes that gravitation is not at the origin of time-asymmetry. Antigravity is just the tidal effect on the vacuum needed to induce the temperature suggested by the “naive” expression of the equivalence principle.

Information is Physical

“The law that entropy always increases holds, I think, the supreme position among the laws of Nature. If someone points out that your pet theory of the universe is in disagreement with Maxwell's equations – then so much the worse for Maxwell's equations. But if your theory is found to be against the second law of thermodynamics, I can give you no hope; there is nothing for it but to collapse in deepest humiliation.”

A.S. EDDINGTON, *“The Nature of the Physical World”*, 1928

In the previous paragraph, we have considered the possibility of extracting photons from the gravitational field and the corresponding evaporation of any massive structure. It seems at first sight that the machine can be reversed and the process used to gradually remove photons initially present in a box. If it were possible to hide such photons at no cost, the Second Law of Thermodynamics would be violated. We want here to suggest that when the information cost of following the annihilation photons on curved spacetime is taken into account, the process cannot be used to violate the Second Law.

Imagine a Maxwell-Wheeler demon trying to violate the Second Law using antigravity. He (or she) intends to hide photons in the vacuum at the minimal cost. Certainly, he must realize his experiment in a box since otherwise he would loose the annihilation photons much too often. The Heisenberg inequalities impose then that the box be large enough to accommodate the wavelength of the photons that he is trying to remove. Calling Δz_{Heis} the minimal size of the box, and λ the photon wavelength, the demon must certainly choose a box such that :

$$\Delta z_{Heis} \geq \lambda = hc/2mg\Delta z_{Heis}$$

or

$$\Delta z_{Heis} \geq \sqrt{\frac{hc}{2mg}} \approx r\sqrt{\frac{r_c}{r_s}} \quad (3)$$

where r_s is the Schwarzschild radius.

The demon must then try to absorb the photons in the most economical way : if he measures too often the position and momentum of the annihilation photons during his attempt to rebuild the $e^+ e^-$ pair, the information cost of such a measurement will more than compensate the disappearance of a third spectator photon. Performing the proposed experiment in the most efficient way requires a *passive* focusing system such as an ellipsoid where the source of positronium would be at the lower focus and the $e^+ e^-$ pair would be reconstructed at the upper focus of the ellipsoid. It then seems that the demon can perform his work completely passively and at no cost. The demon should not forget, however, that he is working on curved spacetime. The amount of information which is needed to perform his experiment can be estimated to be given by the dynamical Kolmogorov-Sinai entropy, conjectured by Pesin [Pes77] to be related to the sum of the positive Lyapounov exponents of the system. The information cost is irreducibly positive if the system is chaotic. Since the orbits of photons in a Schwarzschild geometry are integrable, it seems that the system is not chaotic and that the information cost can be reduced to zero. Thus, it seems at first glance that the transport of photons can be ignored in the entropy balance. In fact, the demon is not dealing with orbits which are infinite but piecewise due to the reflexions needed to reconstruct the original $e^+ e^-$ pair. From the point of view of dynamical system theory, we are left with a billiard enclosing a volume with negative curvature.

The chaotic behaviour of the dynamical system that we are considering is not known but can be justified by the following qualitative argument : a small deviation from a billiard with a regular shape, without chaos, often leads to a chaotic billiard [Zas85]. Here, the billiard without entropy production is the ellipsoid and the perturbation is the curvature of the piece of Schwarzschild metric enclosed by the focusing billiard. Whereas the backfolding of trajectories is the ultimate source of stochasticity, the Lyapounov divergence will be dominated by the curvature. We can then guess that the typical path length defining the Lyapounov exponent for the annihilation photons is given by the Riemann curvature,

$$\Delta z_{Lyap} = O(1)\sqrt{\frac{c^2 r^3}{GM}} = O(1)\, r\sqrt{\frac{r}{r_s}} \quad (4)$$

This parameter means that, given a semi-classical orbit of length l, the information cost that our demon will have to pay to follow the trajectory with a constant precision is approximately given by $l/\Delta z_{Lyap}$ (in bits).

It then appears that using an ellipsoid with the minimal size imposed by Heisenberg inequalities, of typical volume $(\Delta z_{Heis})^3$, our demon would have to pay an information cost (in bits) to eradicate one photon in the fundamental mode (approx. one bit)

$$\Delta z_{Heis} \frac{(\Delta z_{Heis})^3}{(\alpha\ r_c)^3} / \Delta z_{Lyap} = \frac{r^{5/2}}{r_c\ \ r_s^{3/2}\ \alpha^3} > 1 \quad (6)$$

where r_c is the Compton radius, if one uses the two obvious conditions that $r \geq r_c$ and $r \geq r_s$.

Certainly, our argument is still unsatisfying : in particular, the notion of quantum chaos itself is only very partially understood, and our argument is semiclassical. There are in addition a number of fundamental constraints that our demon must take into account : when trying to reset the system, he should care about the limited lifetime of the positronium $\tau_{pos} = 2r_c/c\alpha^5$, (for a disintegration in two photons) and, due to the Unruh effect, always manipulate it with an acceleration much less than

$$g_{max} = \frac{c^2}{\Delta z_{Heis}} \qquad (5)$$

The argument suggests, however :

— that the Second Law can be preserved when the dynamical information cost is taken into account

— and that the fundamental conserved quantity in the problem is entropy or information, a fundamental notion first stressed by Bekenstein [Bek72, 73].

Experimental tests

"Can the recently discovered irreversibility in the decay of a neutral kaon be linked with gravitational and cosmological asymmetries ?"

B. GAL-OR, in *"Modern Developments in Thermodynamics"*, 1974

The previous discussion suggests that we should reconsider the possibility of antigravity; they provide a new motivation for two types of experiments : firstly, direct measurements of the gravitational mass of antiparticles. The PS-200 experiment [Bev86], at the Low-Energy Antiproton Ring (LEAR) at CERN, currently in the stage of installation, proposes to measure, with a precision of the order of 1%, the difference between the gravitational masses of proton and antiproton. However, since the quarks inside the proton carry only a small fraction of its mass, the most clear-cut test of an explicit violation of the equivalence principle would be measuring the gravitational mass of the positron, a tremendously difficult measurement (for a discussion about the experimental problems raised by the measurement of the gravitational mass of antiparticles, see [Dar92]).

A second set of experiments involves the most precise interferometric system at our disposal : the neutral kaon system. It is interesting to note that *all the precision measurements of the ε parameter have involved ultrarelativistic horizontal kaon beams*, with one notable exception. The only experiment for which the angle θ with the horizontal is such that $\gamma \sin\theta$ is not negligible compared to 1 (or, equivalently, for which the energy difference associated with the change in altitude of a kaon during the mixing time of weak interactions is comparable to $\varepsilon \, \Delta m \, c^2$) has led to a determination of the η_{+-} parameter equal to $(2.09 \pm 0.02)\ 10^{-3}$, in disagreement by 9 standard deviations from the world average [Aro83]. In this last experiment, the neutral beam used made an angle of $6.25\ 10^{-3}$ rad with the horizontal, at a typical energy of 70 GeV (average $\gamma \sin\theta \approx 1$). It seems therefore crucial to test whether this non standard result is just due to a coincidence or whether the ε parameter really depends on the direction and momentum of the neutral kaon beam relative to the Earth. In particular, the PS-195 experiment [Adi85], also at LEAR, and currently taking data, should, for the first time, determine with a precision better than 1% the ε parameter for an isotropic kaon "beam" and using kaons in the momentum range [400, 700] MeV/c, generated from the annihilation at rest of a proton with an antiproton. An experiment to measure ε with an inclined kaon beam at Brookhaven is also being studied [Fis92].

Clearly, our hypothesis is equivalent to a regeneration effect and requires that the ε' parameter is zero. In addition, the ε parameter in the B system is predicted to be of the order of 10^{-5}–10^{-6}, from the $m/\Delta m^2$ scaling. These two predictions differ from the Standard Model predictions and provide two further tests of our hypothesis.

Conclusions

In this paper, we have tried to demonstrate that the arguments against antigravity should be reconsidered and that the neutral kaon system, the most sensitive interferometric system at our disposal, is ideal to test the existence of antigravity. We have shown that the Good argument, when expressed in the most natural way, does not exclude antigravity; on the contrary, the Good argument shows that, for a kaon at rest, antigravity would provide just the amount of anomalous regeneration that we observe in the neutral kaon system and that we call CP violation.

Perhaps the most disturbing aspect of antigravity is its apparent violation of energy conservation. But we have stressed that an extremely similar thermal evaporation occurs in the Bekenstein-Hawking radiation of black holes. This leads us to consider that the key quantity when dealing with antigravity is entropy or information. Twenty years ago, the search for the compatibility with the Second Law of Thermodynamics led Bekenstein to the discovery of his relation between mass and entropy, and to the thermal radiation of black holes. In the same spirit, we propose to use the compatibility with the Second Law to establish the relativistic expression of the ε parameter measured in the kaon system, reflecting the divergence of trajectories between a particle and its antiparticle in a gravitational field.

Experimentally, twenty eight years after the experimental discovery of “CP” violation, the CP-LEAR experiment may provide the first precision measurement of the epsilon parameter using an isotropic kaon beam (in a limited momentum range, however). This measurement, together with the measurement of the gravitational mass of the antiproton, is an essential test of General Relativity.

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