QUESTIONING THE EQUIVALENCE PRINCIPLE

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Abstract

The Equivalence Principle (EP) is not one of the "universal" principles of physics (like the Action Principle). It is a heuristic hypothesis which was introduced by Einstein in 1907, and used by him to construct his theory of General Relativity. In modern language, the (Einsteinian) EP consists in assuming that the only long-range field with gravitational-strength couplings to matter is a massless spin-2 field. Modern unification theories, and notably String Theory, suggest the existence of new fields (in particular, scalar fields: "dilaton" and "moduli") with gravitational-strength couplings. In most cases the couplings of these new fields "violate" the EP. If the field is long-ranged, these EP violations lead to many observable consequences (variation of "constants", non-universality of free fall, relative drift of atomic clocks,...). The best experimental probe of a possible violation of the EP is to compare the free-fall acceleration of different materials.

1 Introduction

Newton realized that it is remarkable that all bodies fall with the same acceleration in an external gravitational field, because this means that "weight" (the gravitational interaction) happens to be proportional to "mass" (the universal measure of inertia). However, it took Einstein to fully comprehend the importance of this "equivalence" between weight (gravity) and mass (inertia). In 1907 [1] Einstein introduced what he called the "hypothesis of complete physical equivalence" between a gravitational field and an accelerated system of reference. He used this "equivalence hypothesis" [1, 2] as a heuristic tool to construct a physically satisfactory relativistic theory

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of gravitation. A posteriori, the Einsteinian Equivalence Principle (EP) boils down to the assumption that the gravitational interaction be entirely describable by a universal coupling of matter (leptons, quarks, gauge fields and Higgs fields) to the "metric" tensor $g_{\mu\nu}(x^\lambda)$, replacing everywhere in the matter Lagrangian the usual, kinematical, special relativistic (Minkowski) metric $\eta_{\mu\nu}$. In field theory language, this assumption is equivalent to requiring that the only long-range field mediating the gravitational interaction be a massless spin-2 field. Seen in these terms, we see that the EP is not one of the basic principles of Nature (like, say, the Action Principle, or the correlated Principle of Conservation of Energy). It is a "regional" principle which restricts the description of one particular interaction. An experimental "violation" of the EP would not at all shake the foundations of physics (nor would it mean that Einstein's theory is basically "wrong"). Such a violation might simply mean that the gravitational interaction is more complex than previously assumed, and contains, in addition to the basic Einsteinian spin-2 interaction, the effect of another long-range field. [From this point of view, Einstein's theory would simply appear as being incomplete.] Here, we shall focus on possible additional scalar fields, as suggested by string theory. Gravitational-strength vector fields would also lead to EP violations, though with a different phenomenology.

2 Present experimental tests of the Equivalence Principle

The equivalence principle entails that electrically neutral test bodies follow geodesics of the universal spacetime metric $g_{\mu\nu}(x^\lambda)$, and that all the non-gravitational (dimensionless) coupling constants of matter (gauge couplings, CKM mixing angles, mass ratios,...) are non-dynamical, i.e. take (at least at large distances) some fixed (vacuum expectation) values, independently of where and when, in spacetime, they are measured. Two of the best experimental tests of the equivalence principle are:

(i) tests of the universality of free fall, i.e. of the fact that all bodies fall with the same acceleration in an external gravitational field; and

(ii) tests of the "constancy of the constants".

Laboratory experiments (due notably, in our century, to Eötvös, Dicke, Braginsky and Adelberger) have verified the universality of free fall to better than the 10^{-12} level. For instance, the fractional difference in free fall

acceleration of Beryllium and Copper samples was found to be [3]

$$\left(\frac{\Delta a}{a}\right)_{\text{Be Cu}} = (-1.9 \pm 2.5) \times 10^{-12} \,. \tag{1}$$

See also the work [4] which obtained a $\pm 5.6 \times 10^{-13}$ limit on the difference in free fall acceleration of specially constructed (earth-core-like, and moon-mantle-like) test bodies.

The Lunar Laser Ranging experiment [5] has also verified that the Moon and the Earth fall with the same acceleration toward the Sun to better than one part in 10^{12}

$$\left(\frac{\Delta a}{a}\right)_{\text{Moon Earth}} = (-3.2 \pm 4.6) \times 10^{-13} \,. \tag{2}$$

A recent reanalysis of the Oklo phenomenon (a natural fission reactor which operated two billion years ago in Gabon, Africa) gave a very tight limit on a possible time variation of the fine-structure "constant", namely [6]

$$-0.9 \times 10^{-7} < \frac{e^2_{\text{Oklo}} - e^2_{\text{now}}}{e^2} < 1.2 \times 10^{-7} \,, \tag{3}$$

$$-6.7 \times 10^{-17} \,\text{yr}^{-1} < \frac{d}{dt} \ln e^2 < 5.0 \times 10^{-17} \,\text{yr}^{-1} \,. \tag{4}$$

Direct laboratory limits on the time variation of the fine-structure constant e^2 are less stringent than Eq.(4). For recent results, see Ref. [7]. [See also the claim [8] for a cosmological change of e^2 of the order of one part in 10^5.]

The tightness of the experimental limits (1)–(4) might suggest to apply Occam's razor and to declare that the equivalence principle must be exactly enforced. However, the theoretical framework of modern unification theories, and notably string theory, suggest that the equivalence principle must be violated. Even more, the type of violation of the equivalence principle suggested by string theory is deeply woven into the basic fabric of this theory. Indeed, string theory is a very ambitious attempt at unifying all interactions within a consistent quantum framework. A deep consequence of string theory is that gravitational and gauge couplings are unified. In intuitive terms, while Einstein proposed a framework where geometry and gravitation were united as a dynamical field $g_{\mu\nu}(x)$, i.e. a soft structure influenced by the presence of matter, string theory extends this idea by proposing a framework where geometry, gravitation, gauge couplings, and gravitational couplings

all become soft structures described by interrelated dynamical fields. A symbolic equation expressing this softened, unified structure is

$$g_{\mu\nu}(x) \sim g^2(x) \sim G(x)\,. \tag{5}$$

It is conceptually pleasing to note that string theory proposes to render dynamical the structures left rigid (or kinematical) by general relativity. Technically, Eq. (5) refers to the fact that string theory (as well as Kaluza-Klein theories) predicts the existence, at a fundamental level, of scalar partners of Einstein's tensor field $g_{\mu\nu}$: the model-independent "dilaton" field $\Phi(x)$, and various "moduli fields". The dilaton field, notably, plays a crucial role in string theory in that it determines the basic "string coupling constant" $g_s = e^{\Phi(x)}$, which determines in turn the (unified) gauge and gravitational coupling constants $g \sim g_s$, $G \propto g_s^2$, as exemplified by the tree-level low-energy effective action

$$L_{\text{eff}} = e^{-2\Phi} \left[\frac{R(g)}{\alpha'} + \frac{4}{\alpha'}\,(\nabla\Phi)^2 - \frac{1}{4}\,F_{\mu\nu}^2 - i\overline{\psi}\,D\psi - \ldots \right]\,. \tag{6}$$

A softened structure of the type of Eq. (5), embodied in the effective action (6), implies a deep violation of Einstein's equivalence principle. Bodies of different nuclear compositions fall with different accelerations because, for instance, the part of the mass of nucleus A linked to the Coulomb interaction of the protons depends on the space-variable fine-structure constant $e^2(x)$ in a non-universal, composition-dependent manner. This raises the problem of the compatibility of the generic string prediction (5) with experimental tests of the equivalence principle, such as Eqs. (1), (2) or (4). It is often assumed that the softness (5) applies only at short distances, because the dilaton and moduli fields are likely to acquire a non zero mass after supersymmetry breaking. However, a mechanism has been proposed [9] to reconcile in a natural manner the existence of a *massless* dilaton (or moduli) field as a fundamental partner of the graviton field $g_{\mu\nu}$ with the current level of precision ($\sim 10^{-12}$) of experimental tests of the equivalence principle. The mechanism of [9] (see also [10] for metrically-coupled scalars) assumes that string loop effects modify the effective action (6) by replacing the various factors $e^{-2\Phi}$ by more complicated functions of Φ, e.g. $B_F(\Phi) = e^{-2\Phi} + c_0 + c_1 e^{2\Phi} + \ldots$ Then, the very small couplings necessary to ensure a near universality of free fall, $\Delta a/a < 10^{-12}$, are dynamically generated by the expansion of the universe, and are compatible with couplings "of order unity" at a fundamental level. Refs. [11, 12] discuss possible implementations of this mechanism in certain string models.

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The aim of the present contribution is to emphasize the rich phenomenological consequences of long-range dilaton-like fields, and to compare the probing power of various tests of the EP. For addressing this question we shall (following Refs. [9, 13, 14]) assume, as theoretical framework, the class of effective field theories suggested by string theory.

For historical completeness, let us mention that the theoretical framework which has been most considered in the phenomenology of gravitation, i.e. the class of "metric" theories of gravity [15], which includes most notably the "Brans-Dicke"-type tensor-scalar theories, appears, from a modern perspective, as being rather artificial. This is good news because the phenomenology of "non metric" theories is richer and offers new experimental possibilities. Historically, the restricted class of "metric" theories was introduced in 1956 by Fierz [16] to prevent, in an *ad hoc* way, too violent a conflict between experimental tests of the equivalence principle and the existence of a scalar contribution to gravity as suggested by the theories of Kaluza-Klein [17] and Jordan [18]. Indeed, Fierz was the first one to notice that a Kaluza-Klein scalar would generically strongly violate the equivalence principle. He then proposed to restrict artificially the couplings of the scalar field to matter so as to satisfy the equivalence principle. The restricted class of equivalence-principle-preserving couplings introduced by Fierz is now called "metric" couplings. Under the aegis of Dicke, Nordtvedt, Thorne and Will a lot of attention has been given to "metric" theories of gravity and notably to their quasi-stationary-weak-field phenomenology ("PPN framework", see, e.g., [15]). Note, however, that Nordtvedt, Will, Haugan and others (for references see [15]) studied conceivable phenomenological consequences of generic "non metric" couplings, without using a motivated field-theory framework to describe such couplings.

For updated reviews of the experimental tests of gravity see [19, 20].

3   Generic effective theory of a long-range dilaton

Motivated by string theory, we follow Refs. [9, 13, 14] and consider the generic class of theories containing a long-range dilaton-like scalar field φ. The effective Lagrangian describing these theories has the form (after a conformal transformation to the "Einstein frame"):

$$L_{\text{eff}} = \frac{1}{4q} R(g_{\mu\nu}) - \frac{1}{2q} \left(\nabla\varphi\right)^2 - \frac{1}{4e^2(\varphi)} \left(\nabla_\mu A_\nu - \nabla_\nu A_\mu\right)^2$$

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$$- \sum_A \left[\overline{\psi}_A \gamma^\mu (\nabla_\mu - iA_\mu)\psi_A + m_A(\varphi)\overline{\psi}_A\psi_A \right] + \cdots \tag{7}$$

Here, $q \equiv 4\pi \overline{G}$ where $\overline{G}$ denotes a bare Newton's constant, A_μ is the electromagnetic field, and ψ_A a Dirac field describing some fermionic matter. At the low-energy, effective level (after the breaking of $SU(2)$ and the confinement of colour), the coupling of the dilaton φ to matter is described by the φ-dependence of the fine-structure "constant" $e^2(\varphi)$ and of the various masses $m_A(\varphi)$. Here, A is a label to distinguish various particles. [A deeper description would include more coupling functions, e.g. describing the φ-dependences of the $U(1)_Y$, $SU(2)_L$ and $SU(3)_c$ gauge coupling "constants".]

The strength of the coupling of the dilaton φ to the mass $m_A(\varphi)$ is given by the quantity

$$\alpha_A \equiv \frac{\partial \ln m_A(\varphi_0)}{\partial \varphi_0}, \tag{8}$$

where φ_0 denotes the ambient value of $\varphi(x)$ (vacuum expectation value of $\varphi(x)$ around the mass m_A, as generated by external masses and cosmological history). For instance, the usual PPN parameter $\gamma - 1$ measuring the existence of a (scalar) deviation from the pure tensor interaction of general relativity is given by [21], [9]

$$\gamma - 1 = -2 \frac{\alpha_{\rm had}^2}{1 + \alpha_{\rm had}^2}, \tag{9}$$

where $\alpha_{\rm had}$ is the (approximately universal) coupling (8) when A denotes any (mainly) hadronic object.

The Lagrangian (7) also predicts (as discussed in [9]) a link between the coupling strength (8) and the violation of the universality of free fall:

$$\frac{a_A - a_B}{\frac{1}{2}(a_A + a_B)} \simeq (\alpha_A - \alpha_B)\alpha_E \sim -5 \times 10^{-5}\, \alpha_{\rm had}^2. \tag{10}$$

Here, A and B denote two masses falling toward an external mass E (e.g. the Earth), and the numerical factor -5×10^{-5} corresponds to $A = $ Be and $B = $ Cu. More precisely, dilaton-like models predict a specific type of composition dependence [9, 22] for EP-violating effects. Namely,

$$\left(\frac{\Delta a}{a} \right)_{AB} = \hat{\delta}_A - \hat{\delta}_B, \tag{11}$$

with

$$\hat{\delta}_A = -(\gamma - 1) \left[c_B \left(\frac{B}{\mu} \right)_A + c_D \left(\frac{D}{\mu} \right)_A + 0.943 \times 10^{-5} \left(\frac{E}{\mu} \right)_A \right]. \quad (12)$$

Here μ denotes the mass in atomic mass units, $B \equiv N + Z$ the baryon number, $D = N - Z$ the neutron excess and $E = Z(Z-1)/(N+Z)^{1/3}$ a quantity proportional to nuclear electrostatic energy. The third term on the right-hand-side of Eq. (12) is expected to dominate the other two. Eq. (12) gives a rationale for optimizing the choice of materials in free fall experiments (see Ref. [22] for a detailed discussion).

In addition to modifications of post-Newtonian gravity, such as Eq. (9), and to violations of the universality of free fall, Eq. (10), the Lagrangian (7) also predicts a host of other effects linked to the spacetime variability of the coupling "constants" of physics. Some of these effects are, in principle, measurable by comparing the rates of high-precision clocks based on different time-keepers.

To discuss the probing power of clock experiments, we need to introduce other coupling strengths, such as

$$\alpha_{\text{EM}} \equiv \frac{\partial \ln e^2(\varphi_0)}{\partial \varphi_0}, \quad (13)$$

measuring the φ-variation of the electromagnetic (EM) coupling constant[1], and

$$\alpha_A^{A^*} \equiv \frac{\partial \ln E_A^{A^*}(\varphi_0)}{\partial \varphi_0}, \quad (14)$$

where $E_A^{A^*}$ is the energy difference between two atomic energy levels.

In principle, the quantity $\alpha_A^{A^*}$ can be expressed in terms of more fundamental quantities such as the ones defined in Eqs. (8) and (13). For instance, in an hyperfine transition

$$E_A^{A^*} \propto (m_e \, e^4) \, g_I \, \frac{m_e}{m_p} \, e^4 \, F_{\text{rel}}(Ze^2), \quad (15)$$

so that

$$\alpha_A^{A^*} \simeq 2 \, \alpha_e - \alpha_p + \alpha_{\text{EM}} \left(4 + \frac{d \ln F_{\text{rel}}}{d \ln e^2} \right). \quad (16)$$

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[1]Note that we do not use the traditional notation α for the fine-structure constant $e^2/4\pi\hbar c$. We reserve the letter α for denoting various dilaton-matter coupling strengths. Actually, the latter coupling strengths are analogue to e (rather than to e^2), as witnessed by the fact that observable deviations from Einsteinian predictions are proportional to products of α's, such as $\alpha_A \alpha_E$, α_{had}^2, etc...

Here, the term $F_{\rm rel}(Ze^2)$ denotes the relativistic (Casimir) correction factor [23]. Moreover, in any theory incorporating gauge unification one expects to have the approximate link [9]

$$\alpha_A \simeq \left(40.75 - \ln \frac{m_A}{1 \text{ GeV}} \right) \alpha_{\rm EM} , \qquad (17)$$

at least if m_A is mainly hadronic.

We refer to Refs. [13, 14] for a discussion of various clock experiments within the theoretical framework introduced above. The most promising experiments are the differential "null" clock experiments of the type proposed by Will [15] and first performed by Turneaure et al. [24]. For instance, if (following the suggestion of [25]) one locally compares two clocks based on hyperfine transitions in alkali atoms with different atomic number Z, one expects to find a ratio of frequencies

$$\frac{\nu_A^{A^*}(\mathbf{r})}{\nu_B^{B^*}(\mathbf{r})} \simeq \frac{F_{\rm rel}(Z_A\, e^2(\varphi_{\rm loc}))}{F_{\rm rel}(Z_B\, e^2(\varphi_{\rm loc}))} , \qquad (18)$$

where the local, ambient value of the dilaton field $\varphi_{\rm loc} = \varphi(\mathbf{r})$ might vary because of the (relative) motion of external masses with respect to the clocks (including the effect of the cosmological expansion). The directly observable fractional variation of the ratio (18) will consist of two factors:

$$\delta \ln \frac{\nu_A^{A^*}}{\nu_B^{B^*}} = \left[\frac{\partial \ln F_{\rm rel}(Z_A\, e^2)}{\partial \ln e^2} - \frac{\partial \ln F_{\rm rel}(Z_B\, e^2)}{\partial \ln e^2} \right] \times \delta \ln e^2 . \qquad (19)$$

The "sensitivity" factor in brackets, due to the Z-dependence of the Casimir term, can be made of order unity [25], while the fractional variation of the fine-structure constant is expected in dilaton theories to be of order [9, 13, 14]

$$\begin{aligned} \delta \ln e^2(t) \ = \ & - 2.5 \times 10^{-2}\, \alpha_{\rm had}^2\, U(t) \\ & - \ 4.7 \times 10^{-3}\, \kappa^{-1/2}(\tan \theta_0)\, \alpha_{\rm had}^2\, H_0(t - t_0) . \end{aligned} \qquad (20)$$

Here, $U(t)$ is the value of the externally generated gravitational potential at the location of the clocks, and $H_0 \simeq 0.5 \times 10^{-10}$ yr^{-1} is the Hubble rate of expansion. [The factor $\kappa^{-1/2} \tan \theta_0$ is expected to be ~ 1.]

4 Comparing the probing powers of various experimental tests

We can now use the theoretical predictions given above to compare the probing powers of various experimental tests of relativistic gravity.

Let us first compare post-Newtonian tests to (present) tests of the universality of free fall. Solar-system measurements of the PPN parameter γ, using VLBI measurements [26], constrains (via Eq. (9)) the dilaton-hadron coupling to $\alpha_{\rm had}^2 < 10^{-4}$. By contrast, the present tests of the universality of free fall yields a much better limit. Namely, combining the experimental limit Eq. (1) with the theoretical prediction Eq. (10) shows that the (mean hadronic) dilaton coupling strength is already known to be smaller than:

$$\alpha_{\rm had}^2 \lesssim 10^{-7}\,. \tag{21}$$

If we now consider the constraints coming from the observed lack of variability of the "constants", we find that the best current constraint on the time variation of the fine-structure "constant" (deduced from the Oklo phenomenon), namely Eq. (4), yields from Eq. (20) above, $\alpha_{\rm had}^2 \lesssim 3 \times 10^{-4}$.

Therefore, among present experimental results, the best constraint on dilaton-like models comes from free fall experiments and constrains the basic parameter $\alpha_{\rm had}^2$ to the 10^{-7} level.

Turning our attention from *present* tests to possible *future* tests, let us mention the level of $\alpha_{\rm had}^2$ that they will (hopefully) probe. The Stanford Gyro experiment (Gravity Probe B) will measure soon (via a precise measurement of gravitational spin-orbit effects) $\alpha_{\rm had}^2$ to the 10^{-5} level. The high-precision astrometric mission GAIA should measure γ, and therefore $\alpha_{\rm had}^2$, to the 10^{-7} level. Let us now use the (rough) theoretical prediction (20) to compare quantitatively the probing power of clock experiments to that of free fall tests. Let us (optimistically) assume that clock stabilities of order $\delta\nu/\nu \sim 10^{-17}$ (for the relevant time scale) can be achieved. A differential *ground* experiment (using the variation of the Sun's potential due to the Earth eccentricity) would probe the level $\alpha_{\rm had}^2 \sim 3 \times 10^{-6}$. A geocentric satellite differential experiment could probe $\alpha_{\rm had}^2 \sim 5 \times 10^{-7}$. These levels are interestingly low, but not as low as the present equivalence-principle limit (21). To beat the level (21) one needs to envisage an heliocentric differential clock experiment (a few-solar-radii probe within which two hyperstable clocks are compared). Such an experiment could, according to Eq. (20), reach the level $\alpha_{\rm had}^2 \sim 10^{-9}$. It is, however, to be noted that a much refined free fall test of the equivalence principle such as MICROSCOPE (respectively, STEP) aims at measuring $\Delta a/a \sim 10^{-15}$ (resp. 10^{-18}), which corresponds to the level $\alpha_{\rm had}^2 \sim 10^{-11}$ (resp. 10^{-14}), i.e. two (resp. five) orders of magnitude better than any conceivable clock experiment.

5 Conclusions

In summary, the main points of the present contribution are:

- String theory suggests the existence of new gravitational-strength fields, notably scalar ones ("dilaton" or "moduli"), whose couplings to matter violate the equivalence principle. These fields can induce a spacetime variability of the coupling constants of physics (such as the fine-structure constant).

- The generic class of dilaton theories defined above provides a well-defined theoretical framework in which one can discuss the phenomenological consequences of the existence of a (long-range) dilaton-like field. Such a theoretical framework (together with some assumptions, e.g. about gauge unification and the origin of mass hierarchy) allows one to compare and contrast the probing powers of various experimental tests of gravity. This comparison suggests that free fall experiments are our best hope of probing a small, long-range violation of the Equivalence Principle.

- Let us finally note that, independently of any theoretical prejudice, the recent (probable) discovery that gravity exhibits "repulsive" effects on cosmological scales [27] provides additional motivation for questioning General Relativity on large scales.

References

[1] A. Einstein, *Jahrbuch Radioaktiv.* **4**, 411 (1907).

[2] A. Einstein, *Ann. Phys. Lpz.*, **35**, 898 (1911).

[3] Y. Su et al., *Phys. Rev.* D **50**, 3614 (1994).

[4] S. Baessler et al., *Phys. Rev. Lett.* **83**, 3585 (1999).

[5] J.O. Dickey et al., *Science* **265**, 482 (1994);
    J.G. Williams et al., *Phys. Rev.* D **53**, 6730 (1996).

[6] T. Damour and F. Dyson, *Nucl. Phys.* B **480**, 37 (1996); hep-ph/9606486.

[7] C. Salomon et al., in *Cold Atom Clocks, Proceedings of the International Conference on Atomic Physics 2000*, edited by M. Inguscio and E. Arimondo (World Scientific, Singapore, 2000).

[8] J. K. Webb et al., *Phys. Rev. Lett.* **87**, 091301 (2001).

[9] T. Damour and A.M. Polyakov, *Nucl. Phys.* B **423**, 532 (1994); *Gen. Rel. Grav.* **26**, 1171 (1994).

[10] T. Damour and K. Nordtvedt, *Phys. Rev. Lett.* **70**, 2217 (1993); *Phys. Rev.* D **48**, 3436 (1993).

[11] I. Antoniadis, S. Dimopoulos and A. Giveon, *JHEP*, **0105**, 055 (2001).

[12] M. Gasperini, F. Piazza and G. Veneziano; gr-qc/0108016.

[13] T. Damour , in *Proceedings of the Workshop on the Scientific Applications of Clocks in Space*, edited by Lute Maleki (Jet Propulsion Laboratory publication, 1997) pp 13-21. gr-qc/9711060.

[14] T. Damour , in *Gravitational Waves and Experimental Gravity*, Proceedings of the 34th Rencontres de Moriond, edited by J. Tran Than Van et al. (World Publishers, Hanoi, Vietnam, 2000) pp 357-363. gr-qc/9904032.

[15] C.M. Will, *Theory and experiment in gravitational physics* (Cambridge University Press, 1981); second edition 1993.

[16] M. Fierz, *Helv. Phys. Acta* **29**, 128 (1956).

[17] T. Kaluza, *Sitz. der K. Preuss. Akad. der Wiss.*, 966 (1921);

    O. Klein, *Zeit. für Physik* **37**, 895 (1926).

[18] P. Jordan, *Nature* **164**, 637 (1949); *Schwerkraft und Weltall* (Vieweg, Braunschweig, 1955).

[19] D.E. Groom et al, *Review of Particle Physics*, http://pdg. lbl.gov/, category Astrophysics and Cosmology.

[20] C.M. Will, *Living. Rev. Rel.* **4**, 4 (2001).

[21] T. Damour and G. Esposito-Farèse, *Class. Quant. Grav.* **9**, 2093 (1992).

[22] T. Damour, *Class. Quantum Grav.* **13**, A33 (1996).

[23] H. Kopfermann, *Nuclear Moments* (Academic Press, New York, 1958), pp.123-138;

H.B.G. Casimir, *On the Interaction between Atomic Nuclei and Electrons* (Freeman, San Francisco, 1963), p.54.

[24] J.P. Turneaure et al., *Phys. Rev.* D **27**, 1705 (1983).

[25] J.D. Prestage, R.L. Tjoelker and L. Maleki, *Phys. Rev. Lett.* **74**, 3511 (1995).

[26] T.M. Eubanks et al., "Advances in solar system tests of gravity", preprint available at ftp://casa.usno.navy.mil/navnet/ postscript/, file prd-15.ps.

[27] S. Perlmutter et al., *Astrophys. J* **517**, 565 (1999).

LE PRINCIPE D'ÉQUIVALENCE MIS EN QUESTION

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Abstract

Le Principe d'Équivalence (PE) n'est pas un des principes universels de la physique, mais plutôt une hypothèse heuristique qui restreint le contenu en champ de l'interaction gravitationnelle. La théorie des cordes suggère l'existence de champs scalaires (notablement le dilaton) dont les couplages à la matière "violent" le PE. Les expériences de chute libre apparaissent comme l'outil le plus précis pour mettre en évidence une violation éventuelle (à longue portée) du PE.

En 1907 Einstein introduisit "l'hypothèse de l'équivalence physique complète" entre la gravité et l'inertie. Cette hypothèse heuristique le conduisit à la construction de la théorie de la Relativité Générale. En termes modernes, le "Principe d'Équivalence" (PE) se résume à imposer que le seul champ qui propage l'interaction gravitationnelle soit un champ de spin 2 à masse nulle.

La théorie de la Relativité Générale unifie géométrie et gravitation sous la forme du champ d'espace-temps $g_{\mu\nu}(x^\lambda)$, c.à.d. d'une structure "molle" qui est influencée par la présence de matière. En revanche, la Relativité Générale stipule que toutes les constantes de couplage de la physique sont "rigides", c.à.d. fixées a priori, et indépendantes de la présence de matière. En revanche, en théorie des cordes, toutes les structures physiques (géométrie, gravitation, constantes de couplage) deviennent "molles", c.à.d. décrites par des champs qui varient dans l'espace-temps. Cette variabilité des "constantes de couplage" implique de multiples "violations" du PE : non-universalité de la chute libre, dérive relative des horloges, etc...

En utilisant, comme cadre théorique, une classe de théories décrivant les couplages génériques d'un champ scalaire du type dilatonique on peut décrire la phénoménologie des violations possibles du PE en fonction d'un certain nombre de quantités non dimensionnées, α_A (mesurant le couplage du dilaton à la matière du type A). Ce cadre théorique permet de comparer quantitativement l'"efficacité" avec laquelle diverses expériences (tests de l'universalité de la chute libre, tests des effets post-Newtoniens, comparaison d'horloges, ...) peuvent sonder des violations éventuelles du PE. Cette comparaison indique que les tests de l'universalité de la chute libre (comme

MICROSCOPE ou STEP) sont notre meilleur espoir de détecter une violation éventuelle du PE. Indépendamment de toute théorie, la récente découverte (probable) d'effets gravitationnels "répulsifs" à l'échelle cosmologique donne une motivation supplémentaire pour mettre en question le comportement à longue portée de la gravitation.