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THE GRAVITATIONAL PROPERTIES OF ANTIMATTER

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In classical gravitational physics a particle couples to the local gravitational potential with a strength known as its "gravitational mass"[1,2]. In principle, the gravitational mass is physically distinct from the inertial mass, which is a kinematic property of the particle. Together they determine the particle's gravitational acceleration. There would be no violation of CPT-symmetry if a particle and its antiparticle should fall with different accelerations in the same gravitational potential. (By "gravity" we mean all forces other than the strong, electromagnetic and weak ones of macroscopic range and gravitational strength.) Specifically, CPT-symmetry equates the gravitational acceleration of a particle towards a particular source with that of its antiparticle towards an "anti-source". That is, a proton falls towards the earth with the same acceleration that an antiproton has towards an "anti-earth". CPT does not tell us how an antiproton falls towards our earth. However, a different behavior of an antiproton from a proton in the earth's gravitational field would violate the weak equivalence principle[3] of classical physics. This principle may be expressed mathematically using Newton's inverse-square law,

$$m_I\ g = G\ M_0 m_G / r^2 \qquad (1)$$

for the acceleration, g, of an object of inertial mass m_I, gravitational mass m_G, in the gravitational field of an object of mass M_0. The principle states that,

$$m_I = m_G \quad . \qquad (2)$$

Although incorporated into general relativity, the weak equivalence principle is not an a priori concept, but has been distilled from the results of experiments performed over a 2,000 year period[4]. Indeed, this principle has never been tested for antimatter, and so there is a valid scientific question to be answered: what is the gravitational acceleration of antimatter?[5] (By "antimatter" and "antiparticle" we mean composite objects built out of antiquarks, and antileptons). Furthermore, a generic feature of modern quantum gravity theories is that matter and antimatter have different gravitational properties. In this paper we will argue that a determination of the gravitational acceleration of antimatter (towards the earth) is capable of imposing powerful constraints on such theories.

Various principles of classical physics fail when quantum effects are taken into account. For instance, Newton's first law, which might be re-expressed as "the universality of free-motion"[6], implies that the trajectories of freely-moving particles are determined kinematically in classical physics. This cannot be the case quantum-mechanically because the Heisenberg uncertainty relations involve the momentum, a dynamical quantity.

The classical gravitational analog of Newton's first law is the weak equivalence principle, also known as "the universality of free-fall". It implies that the trajectories of freely-falling classical bodies in a gravitational potential are determined kinematically. This also fails quantum-mechanically[7], as verified by the C-O-W experiment[8]. Furthermore, Wigner[9] has emphasized the incompatibility of general relativity, which embodies weak equivalence, and quantum mechanics. It is therefore not surprising that modern quantum gravity theories, motivated by renormalizability, include interactions of gravitational strength which violate the weak equivalence principle. In order to determine the status of the weak equivalence principle, one must investigate whether these interactions persist in the classical limit, and if so, with what strengths and ranges?[10]

As first noted by Zachos[11], in quantum gravity theories based on local supersymmetry, vector and scalar partners of the graviton appear naturally. Furthermore, vectors and scalars also appear in the reduction to four-dimensions of higher-dimensional gravity theories[12]. Although originally identified with the photon in this last context, it is now clear that the vector is more naturally associated with the graviton. The vector and scalar fields both couple directly to matter. This is quite different from metric theories of gravity, such as the Brans-

Dicke[13] or Hellings-Nordvedt theories[14], in which the new fields do not couple directly to matter. Indeed, the vector field of interest here is reminiscent of the Lee-Yang vector,[15] and will be presumed to couple to some linear combination of baryon and lepton numbers[16]. The new scalar will be somewhat similar to that of Nordström's second theory[17].

The common phenomenology of these quantum gravity theories is the existence of $J = 1$ and 0 partners of the graviton which couple with gravitational strength. The vector is termed the "graviphoton", and the scalar, the "graviscalar[18]. Additional scalar[19] or vector[20] components of gravity have also been suggested in other contexts. The new feature here is the occurrence of both.

New classical effects of gravitational strength, associated with the graviphoton and graviscalar, will arise from the coherent sum over many sources. However, in the static limit of the unbroken theory, with matched couplings, there would be no corrections to Newtonian gravity for ordinary matter from the virtual exchange of the graviphoton and graviscalar[21]. On the other hand, if only the vector were present its coupling would have to be enormously suppressed relative to the graviton[22].

The usual theoretical expectation is that both the graviphoton and graviscalar acquire masses from symmetry breaking. Thus, at the phenomenological level, the observable classical effects of a broad class of quantum gravity theories consist of additional, finite-range (Yukawa) interaction potentials, with approximately gravitational strength. We may expect the ranges to be comparable, and the coupling strength difference to be small. In the linear approximation, the form of the total "gravitational" interaction energy between two massive fermionic objects, separated by a distance r, with four-velocities

$$u_i = \gamma_i(1, \vec{\beta}_i) \tag{3}$$

is then

$$I(r) = - G_\infty \frac{M_1 M_2}{\gamma_1 \gamma_2 r} \times [2(u_1 \cdot u_2)^2 - 1 \mp a(u_1 \cdot u_2)e^{-(r/v)} + b\, e^{-(r/s)}] \tag{4}$$

where a and b are the products (in units of $G_\infty M_1 M_2$) of the vector and scalar charges, and v and s are the inverse masses (in units of length) of the graviphoton and graviscalar, respectively. G_∞ is Newton's constant at infinite separation.

The -(+) sign in front of a in Eq. (4) is chosen for the interaction between matter and matter (antimatter). This arises from the well-known properties of vector boson exchange. The vector component is repulsive between matter and matter (so-called "null"[20] gravity) and attractive between matter and antimatter.

A general prediction of this type of theory is, then, that antimatter would experience a greater gravitational acceleration towards the Earth than matter. Note how different this is from older ideas about "antigravity"[23].

Indeed, there is a general rule of field theory that the exchange of an even-spin particle leads to an attractive force, while the exchange of an odd-spin one produces the rule: "like charges repel, opposites attract"[24]. It is clear that the notion of "antigravity" cannot be accommodated in this framework.

The question immediately arises as to the range of values to be expected for a and b in quantum gravity theories. One would naively expect $a \sim b \sim 1$ for each graviphoton and graviscalar in such theories, and for a simple reduction from 5 to 4 dimensions, there is just one vector and one scalar[21]. However, Scherk has explicitly observed that there could be more than one of each. In particular, we note that for N=8 supergravity, 28 vector and 35 scalar helicity states are present (for each of the two graviton helicity states), raising the possibility that the effective values of a and b are significantly larger than one. (If the scalar does not exist, then b=0.)

Unfortunately, there are no theoretical constraints for the values of v and s. In globally supersymmetric theories, for instance, massive superpartners of massless degrees of freedom may be very light for virtually any value of the supersymmetry breaking vacuum expectation value. Recently, Bars and Visser[25] have argued that the symmetry breaking scale must be related to a vacuum expectation value. This suggests that the weak symmetry breaking scale, Λ, or even the lightest fermion mass, m, may be relevant. Then

$$v^{-1},\ s^{-1} \sim \sqrt{\kappa} \times (m^2,\ \Lambda^2) \qquad (5)$$

where κ is the gravitational coupling constant. From this we conclude that

$$10\text{cm} < v,s < 10^6\text{km} \qquad (6)$$

The naive theoretical expectation, however, is that the graviphoton and graviscalar should have masses $\sim 10^{19}$GeV, although masses of $\sim 10^{-9}$eV may be possible in a geometric hierarchy scheme(26). Meanwhile, in the absence of such an argument, we will adopt a phenomenological approach and turn to gravitational experiments to find bounds on the values of the parameters in Eq. (4).

One classical test would be to search for variations in Newton's constant as a function of the length scale on which it is measured. In fact, the Newtonian limit of gravity has only been tested to a high accuracy at laboratory distance scales, and in the solar system at distances of 10^6 to 10^{13} meters. Deviations from the inverse-square force law are not excluded at intermediate distances(27).

The intermediate region could be tested by experiments such as the Hills' Kepler-Orbit proposal(28). A pair of large spheres, of say 1 meter diameter of dense material, could be placed in high earth orbit to minimize tidal forces, and gravitationally bound to each other. For a 10 meter separation, the period would be on the order of a few days. This would allow a very precise measurement of Newton's constant over a range of distances.

In geophysical experiments, Stacey and co-workers(29,30) have found anomalies which are consistent with deviations from Newtonian gravity on length scales between ~ 1 and $\sim 10^6$ meters. They analyzed their data using only one Yukawa term

$$I(r) = -\frac{G_\infty M_1 M_2}{r}\left[1 + \alpha\, e^{(-r/\lambda)}\right] \quad , \tag{7}$$

and found an effective repulsion with parameters(29,30)

$$1\ \mathrm{m} \lesssim \lambda \lesssim 10^6\mathrm{m} \quad , \tag{8a}$$

$$\alpha = -0.010 \pm 0.005 \quad . \tag{8b}$$

Despite the large uncertainties in Eqs. (8), observation of a definite repulsive component is claimed. However, the measured data is not sufficiently precise to restrict the repulsion to a single Yukawa term. Indeed, the data is consistent with many functional forms(30).

In particular, if a form such as the static limit of Eq. (4) is used,

$$I(r) = -\frac{G_\infty M_1 M_2}{r}\left[1 + a\, e^{(-r/v)} + b\, e^{(-r/s)}\right] \quad , \tag{9}$$

the small effective coupling, α, may be produced by an approximate cancellation between the vector and scalar contributions. This can occur in two ways: there can be a small difference between the values of v and s or there can be quantum corrections which produce a small net difference between the values of a and b.

One could also look for a material dependence of Newton's constant, as did Eötvös, and indeed, Galileo. Recently, Fischbach, et al.(31) found anomalies in the data from the original Eötvös(32) experiment. (Although Dicke and Braginskii(33) verified the weak equivalence principle to a higher accuracy, their experiments were performed with reference to the sun. Therefore, their experiments could well have been unaffected by additional forces of limited range. On the other hand, Eötvös performed his experiment relative to the Earth.) The anomaly was apparently viewed by Eötvös as a systematic effect which was not understood. His quoted error is larger than the uncertainties of the individual points, and in fact is determined by the spread between the points. What Fischbach, et al. found was that the trend of variations is systematic with baryon number, a concept which had not even been invented at the time of Eötvös' experiment!

Although the interpretation of the results as evidence of a (fifth) hyperforce is now controversial, it prompted speculation. A purely theoretical problem with this hypothesis is that an extremely small coupling ($\sim 10^{-2}$ × the gravitational coupling) must be introduced ad hoc. Such a small coupling is difficult to reconcile within the framework of grand unification. While this certainly does not rule out the hypothesis, a gravitational-strength interaction is definitely more natural, because it avoids the necessity of intrinsically small values of a and b.

Aside from the geophysical studies referred to earlier, what other experiments bear on the issue of a new force? Light deflection by the sun(34) does not provide any information, since the interaction(s) do not couple to photons. A variant of an argument due to Good(35), using K_s vacuum-regeneration, would apply if the new interaction coupled differently to strange particles, as Fishbach et al. originally speculated. A gravitational mass difference between K_0 and $\bar{K}_0$ would lead to an anomalous K_s-regeneration from a K_L beam. However, Macrae and Riegert(21) and Scherk(18) all argued that the new gravitational interactions must be family independent, thereby avoiding this problem. Finally, in a recent paper, Lusignoli and Pugliese(36) show that coupling to a non-conserved current (such as strangeness) produces a large branching ratio for the decay, $K^+ \to \pi^+$ plus nothing else observed, in conflict with experimental results.

In an astrophysical context, it could be significant that the graviphoton introduces a new velocity-dependent interaction as shown in Eq. (4). Matter on the surface of a pulsar of radius 10 km, with a period of a msec, has a speed which is a significant fraction of the velocity of light. The graviphoton could yield a significant new repulsive interaction for such high velocities. Since 10 km may well be within the range of the new interactions, they would have to be considered in discussing rapidly rotating pulsars(37) or black holes.

An exciting new possibility is to make a comparison between the gravitational interactions of matter, and of antimatter, with the earth. If the smallness of the observed effects in the matter interactions is due to a cancellation between the vector and scalar terms for matter, then the anomalous effects would add, not cancel, between matter and antimatter. Thus the attraction could be much larger for antimatter, as much as three times the normal gravitational effect, if $a \sim b \sim 1$. A measurement of the gravitational interaction between antimatter and the earth would then be a first-order test of quantum gravity theories, whereas Eötvös-experiments are second-order(18). Indeed, such second-order effects may be absent if the coefficients a and b in Eq. (4) are composition-independent.

An experiment (PS-200) has been recently approved at LEAR(38) to measure the gravitational interaction between matter (the earth) and antimatter(5,39). It takes advantage of the unique availability, at LEAR, of low energy antiprotons. These are to be ejected from LEAR and further decelerated and cooled to ultra-low velocities. They may then be directed up a drift tube for a precise (±0.3%) measurement, using extensions of the techniques pioneered by Witteborn and Fairbank(40). Eötvös-type experiments would be complementary to this experiment, but by no means a substitute for it.

Although we have phrased our discussion in the context of quantum gravity, a measurement of the gravitational acceleration of antimatter is a new, direct test of a fundamental principle (weak equivalence) which has implications beyond any particular class of theories. This principle has never before been tested with antimatter.

We would like to comment on an argument of Morrison(23) and one of Schiff(41) which severely constrained the "antigravity" notion. Although the models discussed in this paper do not embody this concept, it is worthwhile to see if these old arguments impose any constraints on them, since they do involve different gravitational properties of antimatter.

Morrison[23] constructed a gedanken experiment in which he proposed adiabatically lifting a particle-antiparticle pair in a static gravitational field, allowing them to annihilate, and transporting the produced photons down to the initial height. The resulting photon energy must be equal to the rest-energy of the initial pair, plus the energy expended in lifting them. With a conservative gravitational field the "antigravity" idea ran into serious difficulty with this requirement, because the weight of the pair was not equal to the weight of the photons. However, the models discussed here are Lagrangian based, will therefore embody energy-conservation, and so have no difficulty in accommodating Morrison's gedanken experiment.

Schiff[41] argued that virtual antimatter occurs in atoms, and so if "antigravity" existed, it would have been noticeable from the results of the Eötvös experiment. In the models which we have discussed here, the gravitational difference between matter and antimatter arises from the graviphoton, which couples to a conserved charge. Virtual effects cannot change the value of this charge for an atom, and so Schiff's argument imposes no additional constraint.

In summary, there are theoretical reasons to expect, and experimental suggestions of, non-Newtonian non-Einsteinian effects of gravitational strength. In modern quantum gravity theories, only the classical effects of these new interactions are observable at present energies. Typical quantum effects would be expected to be apparent only at the Planck mass scale, $\sim 10^{19}$ GeV. Thus, classical gravitational experiments of the kind we have described here are now at the forefront of modern particle physics. We emphasize that empirical knowledge of the gravitational behavior of antimatter is crucial for a complete understanding.

References

1. G. Burniston Brown, Am. J. Phys. 28, 475 (1960).
2. M. Jammer, "Concepts of Mass", Harvard, Cambridge (1961).
3. R. H. Dicke, "Proc. Int. School Phys. Enrico Fermi, Course 20, G. Polyani ed., Academic, New York (1962).
4. H. C. Ohanian, "Gravitation and Spacetime", Norton, New York (1976).
5. T. Goldman and M. M. Nieto, Phys. Lett. 112B, 437 (1982).

6. J. S. Bell (private communication).

7. D. Greenberger, Ann. Phys. 47, 116 (1968).

8. R. Colella, A. W. Overhauser and S. A. Werner, Phys. Rev. Lett. 34, 1472 (1975).

9. E. P. Wigner, Rev. Mod. Phys. 29, 255 (1957); Bull. Am. Phys. Soc. 24, 633 (1979).

10. T. Goldman, R. J. Hughes and M. M. Nieto, Phys. Lett. 171B, 217 (1968).

11. C. K. Zachos, Phys. Lett. 76B, 329 (1978); Ph.D. Thesis, Caltech (1979).

12. T. Kaluza, Sitz. Preus. Acad. Wiss. K1, 966 (1921); O. Klein, Zeit. Phys. 37, 895 (1926).

13. C. Brans and R. H. Dicke, Phys. Rev. 124, 925 (1981).

14. R. W. Hellings and K. Nordvedt, Phys. Rev. D7, 3593 (1973).

15. T. D. Lee and C. N. Yang, Phys. Rev. 98, 1501 (1955).

16. T. Goldman, R. J. Hughes, and M. M. Nieto, LA-UR-86-3617, Submitted to Phys. Rev. D.

17. G. Nordström, Ann. Phys. 42, 533 (1913), 43, 1101 (1914); A. L. Harvey, Am. J. Phys. 33, 449 (1965).

18. J. Scherk, La Recherche 8, 878 (1977); Phys. Lett. 88B, 265 (1979); in "Unification of the Fundamental Particle Interactions" eds., S. Ferrara, J. Ellis and P. van Nieuwenhuizen, Plenum, NY (1981).

19. Y. Fujii, Nature Phys. Sci. 234, 5 (1971); J. O'Hanlon, Phys. Rev. Lett. 29, 137 (1972); A. Zee, Phys. Rev. Lett. 42, 417 (1979).

20. P. Fayet, Phys. Lett. 171B, 261 (1986); L. B. Okun, Sov. Phys. JETP 56, 502 (1982).

21. K. I. Macrae and R. J. Riegert, Nucl. Phys. B244, 513 (1984).

22. R. H. Dicke, Phys. Rev. 126, 1580 (1962); L. B. Okun, Sov. J. Nucl. Phys. 10, 206 (1969).

23. P. Morrison, Am. J. Phys. 26, 358 (1956).

24. D. C. Peaslee, Science 124, 1292 (1956); K. Jagannathan and L. P. S. Singh, Phys. Rev. D33, 2475 (1986).

25. I. Bars and M. Visser, Phys. Rev. Lett. 57, 25 (1986).

26. S. Raby, private communication

27. D. R. Mikkelsen and M. J. Newman, Phys. Rev. D16, 919 (1977); G. W. Gibbons and B. F. Whiting, Nature 291, 636 (1981); P. Hut, Phys. Lett. 99B, 174 (1981).

28. J. G. Hills, A. J. 92, 986 (1986).

29. F. D. Stacey, G. J. Tuck, S. C. Holding, A. R. Maher, and D. Morris, Phys. Rev. D23, 1683 (1981); F. D. Stacey and C. J. Tuck, Nature 292, 230 (1981); S. C. Holding and G. J. Tuck, Nature 307, 714 (1984); F. D. Stacey, p. 285 in Science Underground, M. M. Nieto, W. C. Haxton, C. M. Hoffman, E. W. Kolb, V. D. Sandberg, and J. W. Toevs, eds., (AIP, New York, 1983), AIP Conference Proceedings no. 96.20.

30. S. C. Holding, F. D. Stacey, and G. J. Tuck, Phys. Rev., D33, 3487 (1986).

31. E. Fischbach, D. Sudarsky, A. Szafer, C. Talmadge, and S. H. Aronson, Phys. Rev. Lett. 56, 3 (1986).

32. R. V. Eötvös, D. Pekár, and E. Fekete, Ann. Phys. (Leipzig) 68, 11 1922).

33. P. G. Roll, R. Krotkov and R. H. Dicke, Ann. Phys. (NY) 26, 442 (1964); R. H. Dicke, Sci. Am. 205, 84 (December 1961); V. V. Braginskii and V. I. Panov, Sov. Phys. JETP 34, 463 (1972).

34. F. W. Dyson, A. S. Eddington, and C. Davidson, Phil. Tran. Roy. Soc. A220, 291 (1919).

35. M. L. Good, Phys. Rev. 121, 311 (1961).

36. M. Lusignoli and A. Pugliese, Phys. Lett. 171B, 468 (1986).

37. T. Goldman, R. J. Hughes, and M. M. Nieto (in preparation).

38. N. Beverini et al., "A measurement of the gravitational acceleration of the antiproton", LANL report LA-UR-86-260 (1986).

39. J. H. Billen, K. R. Crandall, and T. P. Wangler, in Physics with Antiprotons at LEAR in the ACOL Era, U. Gastaldi, R. Klapisch, J. M. Richard, and J. Tran Thanh Van, eds. (Editions Frontieres, Gif sur Yvette, France, 1985), p. 107; T. Goldman and M. M. Nieto, ibid, p. 639; M. V. Hynes, ibid, p. 657.

40. F. C. Witteborn and W. M. Fairbank, Phys. Rev. Lett. 19, 1049 (1967); Rev. Sci. Inst. 48, 1 (1977); Nature 220, 436 (1968).

41. L. I. Schiff, Proc. Nat. Acad. Sci. 45, 69 (1959); Phys. Rev. Lett 1, 254 (1958).