GRAVITATIONAL PROPERTIES OF ANTIMATTER: EXPERIMENTAL EVIDENCE FOR QUANTUM GRAVITY?

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Einstein's theory of gravity, when treated as a quantum field theory, diverges at the one-loop level if matter fields are included. Early attempts to remedy this divergence were built on the analogy of the Riemann-Christoffel tensor ($R^{\lambda}{}_{\mu\nu\sigma}$) to the gauge covariant curl ($F^{\lambda}{}_{\mu ab}$) in a gauge theory: The Lorentz ($\nu\sigma$) and internal symmetry indices (ab) were identified. Then a Lagrangian density formed from the Ricci tensor, the metric tensor and Newton's constant (κ)

$$(R_{\mu\nu} + \kappa g_{\mu\nu})^2 = R^2 + 2\kappa R + \kappa^2 \tag{1}$$

is both analogous to the well-behaved F^2 of a gauge theory, and the cross term is just Einstein gravity.

However, as Macrae[1] emphasized, one must now explicitly exclude torsion in space-time to avoid the appearance of an apparently unwanted, additional vector field. With the advent of local supersymmetry, as first noted by Zachos[2], both vector and scalar partners of the graviton naturally appear. Later analysis showed these theories to have improved renormalization properties.

The relationship between $N = 8$ supersymmetry in $D = 4$-dimensional space-time to an $N = 2$, $D = 10$ theory prompted a renewal of attention to the ideas of

Kaluza and Klein[3]. They had suggested that if a D = 5 metric tensor were reduced to a D = 4 tensor by requiring a small radius of curvature in the fifth dimension, then a vector and scalar field would also appear in the D = 4 space, as leftover pieces of the D = 5 metric tensor. Although their original aim was to identify the vector with the photon, it is clear now that it is more naturally a new field, partner to the graviton.

Now we also have superstring theories[4] with even better renormalization properties, in D = 10 + 16 dimensions, and which may predict the spectrum of light particles (quarks and leptons and gauge bosons) as string zero-modes. There will also be, perhaps hundreds of, spin one and zero partners of the graviton, coupling with gravitational strength.

Although the improving renormalization properties have encouraged these efforts, they are still just theoretical constructs. The question arises: How can they be tested?

In the unbroken theory, the extra bosons couple with precisely gravitational strength, and are massless. Despite their zero masses, they would not be apparent in ordinary particle physics scattering experiments, because of this small coupling strength. Scattering amplitudes due to virtual exchanges of these bosons are 34 orders of magnitude smaller than weak interaction amplitudes, and their rate of (bremsstrahlung) radiation is comparable to that for gravitons. Thus, to see effects of these bosons at ordinary energies requires a coherent sum over many sources, thereby producing effects at the classical level. One might alternatively look for: More exotic superpartners of the known fields[5] such as scalars with quantum numbers of ordinary fermions (sfermions) or spin one-half particles with gauge or Higgs' boson quantum numbers (gauginos, higgsinos); or new repetitions (families) of quarks and leptons predicted by these theories. However, such discoveries would really only argue for a supersymmetry or for a larger gauge group of the ordinary sort. They do not specifically support quantum gravity.

The common phenomenology of these quantum gravity theories is the existence of $J = 1$ and 0 partners of the graviton that couple with gravitational strength. (The additional fermions have less obvious effects.) The vector boson is termed[6] the "graviphoton" and the scalar is the "graviscalar". The former couples to some conserved current (like the fermion number current) and the latter to the trace of the stress-energy tensor.[6]

In the static limit of the unbroken theory, there would be no corrections to Newtonian gravity from virtual exchanges of the vector and scalar bosons, as their effects would exactly cancel for ordinary matter. Further, if only the vector boson exists, it would exactly cancel the usual tensor gravitational interaction due to graviton exchange. The latter is obviously inconsistent with experience. The former is unlikely to occur, since it is known that if supersymmetry does exist, it must be a broken symmetry[5]. Then, the usual theoretical expectation is that both the graviphoton and the graviscalar acquire masses from this symmetry breaking. Symmetry breaking also allows quantum-loop corrections to produce violations of the universal coupling property which may be small.

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 differences 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,

$$u_i = \gamma_i(1, \vec{\beta}_i) \tag{2}$$

is then

$$I(r) = - G_\infty \frac{M_1 M_2}{\gamma_1 \gamma_2 r} \tag{3}$$

$$\times [2(u_1 \cdot u_2)^2 - 1 \mp a(u_1 \cdot u_2) e^{-(r/v)} + b\, e^{-(r/s)}]$$

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. (3) is chosen for the inter-action 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"[7] or "anti"[6] gravity) and attractive between matter and antimatter.

A general prediction of this type of theory is, then, that anti- matter would experience a greater gravitational acceleration towards the Earth than matter. This clearly violates the weak equivalence principle, but not CPT, as only part of the system has been conjugated. Note how different this is from older ideas about "antigravity"[8].

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[7]. However, Scherk[6] 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[9] have argued that the symmetry breaking scale must be related to a vacuum expectation value, because the current to which the graviphoton couples is not related to the four-momentum current. This suggests that the weak scale symmetry breaking, Λ, or even the lightest fermion mass, m, may be relevant. Then

$$v^{-1}, s^{-1} \sim \sqrt{\kappa} \times (m^2, \Lambda^2) \tag{4}$$

from which we conclude that

$$v, s \in (10 \text{ cm}, 10^6 \text{ km}) \tag{5}$$

In fact, their are values only constrained by experiment[5]. Thus we must turn to gravitational experiments to find bounds on the values of the parameters in Eq. (2).

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[10].

The intermediate region could be tested by experiments such as the Hills' Kepler-Orbit proposal[11]. 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[12,13] have found anomalies which are consistent with deviations from Newtonian gravity on length scales between ∿1 and ∿10^6 meters. They analyzed their data using only one Yukawa term,

$$I(r) = - \frac{G_\infty M_1 M_2}{r} [1 + \alpha e^{(-r/\lambda)}] , \tag{6}$$

and found an effective replusion with parameters [18,22]

$$1 \text{ m} \lesssim \lambda \lesssim 10^6 \text{m}, \tag{7a}$$

$$\alpha = -0.010 \pm 0.005 . \tag{7b}$$

Despite the large uncertainties in Eqs. (7), 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[13].

In particular, if a form such as the static limit of Eq. (3) is used,

$$I(r) = - \frac{G_\infty M_1 M_2}{r} [1 \mp a e^{(-r/v)} + b e^{(-r/s)}] , \tag{8}$$

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 differerce between the values of a and b.

Once could also look for a material dependence of Newton's constant, as did Eötvös, and indeed, Galileo. Recently, Fischbach, *et al.*[14] found anomalies in the data from the original Eötvös[15] experiment. (Although Dicke and Braginskii[16] 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 this analysis is now controversial, it prompted speculation about a new, "fifth force". 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 arising from a symmetry partner of the usual gravitational 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 reflect on this question? The Pound-Rebka experiment[17] or light deflection by the sun[18] do not provide any information either, since the new interaction(s) do not couple to photons. A variant of an argument due to Good[19], using K_s-vacuum-regeneration, would apply if the new interaction coupled differently to strange particles, as Fishbach *et al.* originally speculated. The observed CP-violation in the neutral kaon system requires the K^0 and $\bar{K}^0$ components of a K_L wave packet to remain superposed. However, they would separate by a few fermis in several Lorentz-dilated lifetimes if there were differing gravitational strength forces on the two components. Since coherence is evident over such lengths, the difference must be small. This can be satisfied if the difference of differences between the effects on s and $\bar{d}$ quarks and on $\bar{s}$ and d quarks is small. Indeed, Macrae and Riegert[7] and Scherk[6] all argued that the new gravitational interactions must be family independent. Finally, in a recent preprint, Lusignoli and Pugliese[20] 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. (3). 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 or black holes.

Similarly, as Macrae and Riegert[6] noted, a rapidly rotating ring on the surface of the Earth would experience a repulsive force from the Earth in addition to the normal gravitational attraction. In the limit of long range, the effective coupling constant is

$$G = G_\infty M_1 M_2 [2\gamma^2 - 1 \mp a\gamma + b] \quad . \tag{9}$$

where the -(+) sign refers to matter (antimatter). For $a \sim b \sim 1$, this could produce a measurable effect, if the range were indeed long enough.

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 $a \sim b \sim 1$.

An experiment (P-94) has been recently approved at LEAR to measure the gravitational interaction between matter (the earth) and antimatter[21]. 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[22]. This would be a first-order test of quantum gravity theories, whereas an Eötvös-type experiment is of second order.

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. The question arises because weak equivalence is a classical statement from general relativity, which is based on the definition of trajectories for particles. To connect it to antimatter, however, requires the use of CPT-symmetry, which invokes quantum mechanics (through quantum field theory). But, the latter explicitly forbids the definition of trajectories! We may speculate that this conflict in basic assumptions[23] is related to the apparent need to introduce non-metric components of gravity to improve the renormalization properties of quantum gravity.

Because of these extra components, a violation of weak equivalence for antimatter does not necessarily imply a violation of CPT-invariance. But can this be done? There have been recent speculations that CPT-violation must, in a cosmological context, e.g., from the effects of Hawking radiation converting pure states to mixed states. There is clearly a connection to gravity and non-flat spacetime, wherein the CPT theorem is not proved.

To show that violating CPT in a curved space is not inconceivable, we consider the following model: A charged particle in a uniform magnetic field, B, but with the two transverse dimensions compactified. The remaining one-dimensional space may be thought of as running along a field line. Since B is constant, there is no remaining overt evidence of it in the subspace. The spectrum of states is given by

$$\omega = \sqrt{(2n+1)eB + geBs_z + m^2 + k_z^2}$$

$$\text{and} \qquad = -\sqrt{(2n+1)eB - geBs_z + m^2 + k_z^2} \qquad (10)$$

where m is the mass, k_z the z-component of momentum, s_z is the z-component of spin, $g \simeq 2$ and ω_n is the eigen-energy. In three-space, a $s_z = +1/2$ positive energy state has a CPT-conjugate partner negative energy state at $s_z = -1/2$, with the identical magnitude for ω_n. In the reduced space, however, one may keep only the $s_z = +1/2$ states. For $B = 0$, this is a normal system, but for $B \neq 0$, the natural negative energy state conjugate to a given state has a different magnitude of ω_n due to the spin term. This form of CPT-violation appears similar to spontaneous symmetry breaking: The symmetry is exact in the underlying theory, but appears broken due to an asymmetric vacuum state.

Finally, I would like to comment on an energy conservation type argument first raised by Morrison[8], with regard to the viability of different gravitational interactions of matter and antimatter. Supergravity theories provide a direct counter-example to the notion that these pure thought arguments can rule out unusual effects; nonetheless, it is interesting to see the point directly.

Suppose that the gravitational mass, m_G, for a particle is

$$m_G = m_I + d \qquad (11)$$

and for an antiparticle, $\bar{m}_G$, is

$$\bar{m}_G = m_I + f \tag{12}$$

where m_I is the common (by CPT) inertial mass. If we raise the pair a distance ℓ in the earth's field, characterized by acceleration g, let them annihilate into photons, and drop the photons back to the starting point, then the known blue-shift[17] of the photons and energy conservation require

$$d + f = 0 \tag{13}$$

This is exactly what occurs for the vector contribution in the quantum gravity theories.

While the vector and tensor pieces are contrained to this by general covariance and gauge invariance, the scalar piece is not. The result above depends on there being no meaning to an absolute potential. For this to apply to the scalar would require dilatation invariance, which is always violated by renormalization. Thus, there may be an absolute scalar potential, and Morrison-type arguments cannot be used on this component.

In summary, there are theoretical reasons to expect, and experimental suggestions of, non-Newtonian non-Einsteinian effects of gravitational strength. In modern quantum 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 on antimatter 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.

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