Does Antimatter Fall with the Same Acceleration as Ordinary Matter?

E. G. Adelberger, B. R. Heckel, C. W. Stubbs,[a] and Y. Su
Physics Department, FM-15, University of Washington, Seattle, Washington 98195
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Equivalence-principle experiments with ordinary matter probe the gravivector acceleration of antimatter in the same way as do direct measurements of antimatter in free fall and set stringent upper limits on the gravivector acceleration of antimatter predicted by certain "quantum-gravity" models.

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There has been much speculation about the response of antimatter to gravitational fields. According to general relativity a particle and its antiparticle should have identical accelerations in a given gravitational field. However, it has been argued[1-3] that attempts to build quantum theories of gravity naturally lead to additional gravitational forces, mediated by spin-0 and spin-1 partners of the conventional spin-2 graviton that produces the familiar gravitational effects. If these partners have sufficiently low masses, the forces they generate will have ranges long enough to produce interesting effects in the macroscopic world. In any[4] field theory the exchange of even-spin bosons (such as the ordinary graviton or its proposed spin-0 partner) between unpolarized particles of the same kind generates attractive forces, while the exchange of odd-spin bosons (such as the photon or the proposed spin-1 graviton) leads to forces that are repulsive. Consequently, it has been noted[3] that in the everyday world consisting of ordinary matter, the attractive graviscalar and repulsive gravivector interactions could essentially cancel and thus may have escaped detection. For antimatter the situation would be strikingly different. As the particle-antiparticle forces generated by both scalar and vector interactions are attractive, an antiparticle in the gravitational field of the Earth would experience graviscalar and gravivector interactions that were both attractive, and thus could fall with an acceleration greater than g.

It is not easy to test this idea directly. Some twenty years ago Witteborn and Fairbank,[5] intending ultimately to measure the force of gravity on positrons, attempted to measure the gravitational acceleration of electrons. They encountered severe problems, discovering that it is virtually impossible to reduce electric fields to a negligible level (an electric field of only 6×10^{-11} V/m gives an electron an acceleration equal to that of gravity). The antiproton, with a mass of $\approx 2000 m_e$, feels a correspondingly greater gravitational force and is thus less affected by small electric fields. An experiment[3] to measure the gravitational acceleration of antiprotons to a precision of $0.01g$ is being prepared for the Low Energy Antiproton Ring (LEAR) at CERN. The electric-field problem would be bypassed in a proposed[6] measurement of the gravitational acceleration of antihydrogen atoms.

Because it has proved very difficult to obtain a precise result using direct means, it is worth asking if one can test for the proposed effects indirectly. It might be thought that the tight constraints[7,8] on gravitational splitting of the K^0 and $\bar{K}^0$ mesons rule out scalar or vector gravitons. This is not the case as a spin-1 graviton coupled to baryon number or lepton number would cause an antiproton or positron to fall with an acceleration different from g without producing *any* effect in the neutral-kaon system. On the other hand, we argue that equivalence-principle (EP) experiments[9-12] rule out gravivector interactions at roughly the $10^{-6}g$ level. Our argument differs from ones given previously by Morrison[13] and Schiff,[14] who focused on the virtual antiparticle content of ordinary matter, and has the advantage that the relevant quantities can be more easily calculated in our approach.

Our reasoning, in a nutshell, is this. If antimatter falls with an acceleration different from that of matter, it must be due to a vector interaction because the scalar and tensor interactions of a particle are identical to those of its antiparticle. (We limit discussion to gravitons with spins ≤ 2.) The acceleration of a test particle due to a macroscopic vector force is proportional to q_V/m, the "vector-charge"-to-mass ratio of the particle. The most general vector charge of matter composed of the first-generation fermions contains terms proportional to the numbers of protons, neutrons, and electrons,

$$q_V = q_p(N_p - N_{\bar{p}}) + q_n(N_n - N_{\bar{n}}) + q_e(N_{e^-} - N_{e^+}), \quad (1)$$

where, for example, q_p is the gravivector charge of the proton and N_p refers to the number of protons in a test body.

The Earth's gravivector field $\mathbf{V}$ will give a test particle an acceleration

$$\mathbf{a}_V = \mathbf{F}_V/m = (q_V/m)\mathbf{V}. \quad (2)$$

(We assume throughout that the range of the gravivector interaction is much greater than the size of the apparatus so that $\mathbf{V}$ can be treated as a uniform field.) Now consider measurements of the gravitational acceleration of antiprotons, positrons, antihydrogen, and antineutrons. The first two experiments involve charged particles and require electromagnetic shielding to avoid spurious electrical or magnetic effects. However, as pointed out by Schiff and Barnhill[15] and observed by Witteborn and Fairbank,[5] the shields affect the acceleration of the test particle. The free electrons in the shield respond to the gravitational fields by arranging themselves to produce an electric field $\mathbf{E}$ that just cancels the gravitational force on the electrons in the conductor:

$$\mathbf{F}_e = m\mathbf{g} + q_e\mathbf{V} - e\mathbf{E} = 0, \quad \mathbf{E} = \frac{m\mathbf{g} + q_e\mathbf{V}}{e}, \tag{3}$$

where m and $-e$ are the electron's mass and electrical charge. An antiproton placed inside a conducting shield will experience an acceleration

$$\mathbf{a}_{\bar{p}} = \frac{\mathbf{F}}{M} = \frac{M\mathbf{g} - q_p\mathbf{V} - e\mathbf{E}}{M} = \mathbf{g}\frac{M-m}{M} - \mathbf{V}\frac{q_p + q_e}{M}, \tag{4}$$

where M is the proton mass. On the other hand, a positron will receive an acceleration

$$\mathbf{a}_{e^+} = \frac{m\mathbf{g} - q_e\mathbf{V} + e\mathbf{E}}{m} = 2\mathbf{g} \tag{5}$$

that is not sensitive to the gravivector interaction. The electrically neutral antihydrogen and antineutron will accelerate respectively with

$$\mathbf{a}_{\bar{\mathrm{H}}} = \mathbf{g} - \mathbf{V}\frac{q_p + q_e}{M+m} \tag{6}$$

and

$$\mathbf{a}_{\bar{n}} = \mathbf{g} - \mathbf{V}q_n/M_n. \tag{7}$$

It is easy to verify that the corresponding experiments with particles instead of antiparticles have precisely the same sensitivities to the gravivector interaction. Such experiments, therefore, are sensitive to only *two* quantities: $q_p + q_e$ and q_n. Although we have considered the case of electrostatically shielded particles, the results are quite general. In the absence of shielding the above experiments are sensitive to three quantities, $q_p\mathbf{V} + e\mathbf{E}$, $q_e\mathbf{V} - e\mathbf{E}$, and $q_n\mathbf{V}$, which reduce to the shielded case upon eliminating the dependence on the unknown ambient field $\mathbf{E}$.

Now consider the effect of the gravivector interaction on a Galileo-type EP experiment. The differential acceleration of the electrically neutral test bodies will be

$$\Delta\mathbf{a} = \Delta\left(\frac{\mathbf{F}}{M}\right) = \frac{\mathbf{V}}{M_0}\left[(q_p + q_e)\Delta\left(\frac{Z}{\mu}\right) + q_n\Delta\left(\frac{N}{\mu}\right)\right], \tag{8}$$

where Z and N are the proton and neutron numbers of the test bodies, and $\mu = M/M_0$ is the test-body mass in atomic mass units. Because the number of protons, neutrons, or baryons per atomic mass unit varies significantly from one material to another, EP experiments are sensitive to the *same two quantities* as the hypothetical set of antimatter experiments mentioned above. Of course, the gravivector signal in EP experiments is typically smaller than in, say, an antiproton experiment. The least favorable case occurs if $q_p = q_n$ and $q_e = 0$ so that $q_V = B$, where B is the baryon number. Then the antiproton has $|q_V/\mu| = |B/\mu| \approx 1$ while the pair of materials in an EP experiment has $|\Delta(B/\mu)| \sim 10^{-3}$. However, the EP experiments can be done with very high precision. For example, it has recently been found[9] that Be and Cu ($\Delta B/\mu \approx 2.47\times 10^{-3}$) have "gravitational" accelerations in the Earth's field which are identical to ≈ 1 part in 10^{11}.

Could the EP experiments have failed to detect a gravivector force because it was canceled by a graviscalar interaction?[16] This might have occurred (although it would be a very improbable accident that the cancellation was so precise) if the experiments had compared the accelerations in the Earth's field of a single pair of materials. However, exact cancellation *cannot* occur for a range of test materials because of the inherently different nature of scalar and vector charges. The accelerations in the Earth's field of numerous pairs of materials have been compared with high precision: among them are Be/Al,[9] Be/Cu,[9] Cu/U,[10] C/Al,[11] and Al/Cu.[11] For interactions with ranges $\gtrsim 10^{11}$ m, we obtain a sixth constraint from the comparison of Al/Pt in the field of the Sun.[12] As no anomalous accelerations were seen in any of these tests and no confirmed violations of the gravitational $1/r^2$ law have been detected, we can essentially exclude the possibility that a significant gravivector interaction was canceled by a graviscalar force.

Let us review this argument. Graviscalar and gravivector forces would produce a potential between a pair of test bodies of the form

$$V_{12}(r) = -\frac{g_S^2}{4\pi}(q_S)_1(q_S)_2\frac{\exp(-r/\lambda_S)}{r} + \frac{g_V^2}{4\pi}(q_V)_1(q_V)_2\frac{\exp(-r/\lambda_V)}{r}, \tag{9}$$

where g_S and g_V are graviscalar and gravivector coupling constants presumed[3] to be of roughly gravitational strength, λ_S and λ_V are the ranges of the graviscalar and gravivector forces, and q_S and q_V are the scalar and vector changes of the test bodies. These charges differ in fundamental ways. A vector charge has no contribution from binding energy, while a scalar charge, in general, does (this follows from the properties of the charges under the particle-antiparticle transformation). A vector charge of a composite system is unaffected by the motion of its constituents, while a scalar charge, in general, is. (A vector charge is Lorentz invariant, but a scalar charge contains a factor of $1/\gamma = [1-(v/c)^2]^{1/2}$.) Because binding energy and $1/\gamma$ are not linear functions of Z and N, q_S cannot be exactly proportional to q_V.

The general form of q_V was discussed above. It is more difficult to specify q_S. Although the scalar couplings may be simple in terms of the fundamental fields (for example, the expectation value of the total number of quarks plus antiquarks), q_S of a neutral atom reflects its complex structure and may depend in a complicated fashion on the atomic and nuclear binding energies. We therefore characterize q_S of stable, electrically neutral matter with the expression

$$q_S = q_S(\mu, |B|/\mu, |L|/\mu), \tag{10}$$

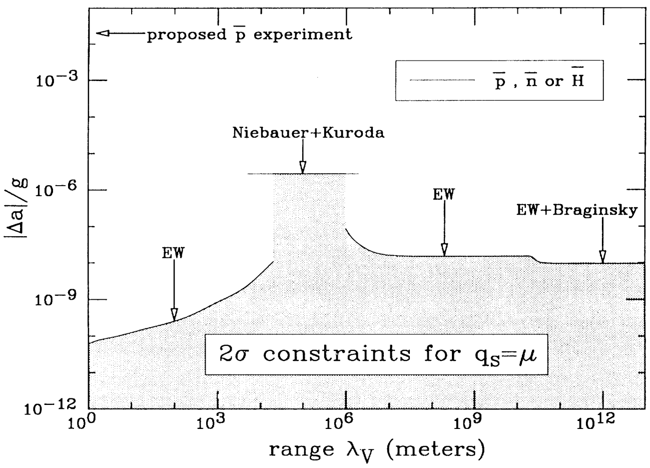

FIG. 1. Constraints on the gravivector acceleration of antineutrons, antihydrogen, and electrically shielded antiprotons (in units of $g=980$ cm/s^2) for the case where $q_S=\mu$. The three constraints are not identical, but differences cannot be resolved on this plot. The gravivector acceleration of electrically shielded positrons is not shown as it must vanish. The unshaded region is excluded by equivalence-principle data on at least two pairs of materials. This eliminates the possibility that a null effect was due to an accidental vanishing of $\Delta(q_V/\mu)$ for a particular pair of materials. Vertical accelerations in free-fall experiments were analyzed using the Earth model given in Ref. 18 (assuming that experiments were conducted 1.5 m above the Earth's surface). Horizontal accelerations in the Eöt-Wash experiment were computed as described in Ref. 9. The horizontal arrow shows the anticipated precision of a proposed direct measurement of the antiproton acceleration.

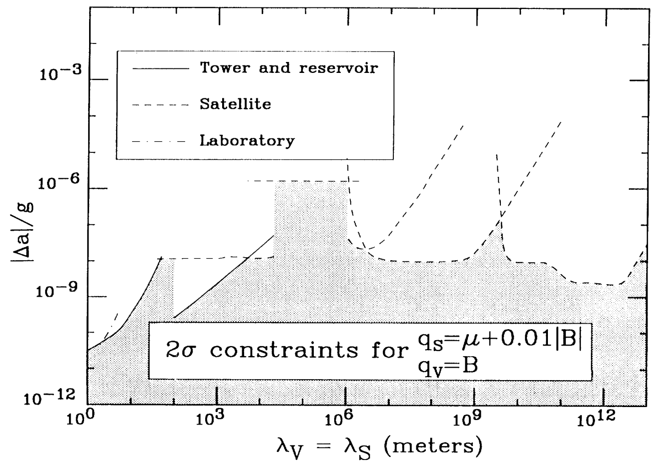

FIG. 2. Constraints on the gravivector acceleration of electricity shielded antiprotons (in units of g) for the case where $q_S \approx \mu+0.01|B|$ and $q_V=B$. For simplicity, we assume that $\lambda_S=\lambda_V$. These constraints were obtained by combining equivalence-principle data with results of astronomical, laboratory, and geophysical tests of the $1/r^2$ law. Gravivector and graviscalar interactions can be separated because the inverse-square experiments are sensitive to the leading term (μ) in q_S and the equivalence-principle results are not. The unshaded region is excluded.

where B and L are the baryon and lepton numbers. Now consider various possibilities for q_S.

(1) q_S does not depend on $|B|/\mu$ or $|L|/\mu$, i.e., $q_S=\mu$. In this case the graviscalar couples to T^μ_μ, the trace of the energy-momentum tensor, as in the Brans-Dicke theory.[17] Because the scalar interaction couples identically to mass it will not contribute to the differential acceleration of test bodies. Then EP experiments "feel" the entire gravivector interaction and are completely unaffected by the graviscalar force. Using constraints on $g_V^2/4\pi$ as a function of λ_V obtained from the results of Ref. 9, we infer that any observable gravivector acceleration of antimatter is less than $2\times10^{-6}g$. These constraints are shown in Fig. 1.

(2) q_S depends weakly on $|B|/\mu$ and/or $|L|/\mu$, i.e., $q_S \approx \mu[1+\epsilon(|B|/\mu,|L|/\mu)]$ with $\epsilon \ll 1$. This scenario, in which the scalar couples primarily to mass with small corrections due to atomic and nuclear structure, has been discussed by Peccei, Sola, and Wetterich.[19] In this case, approximate cancellation of the scalar and vector forces in EP experiments can occur only if $\epsilon \propto |q_V/\mu|$ and $g_V^2\mathbf{I}_V \approx \epsilon g_S^2 \mathbf{I}_S$, where the **I**'s are integrals of $\nabla V_{12}(r)$ over the source (which, except for Ref. 12, is the Earth). For small ϵ, the main effect of the graviscalar interaction is composition independent and detectable (assuming that λ_S is not greater than planetary distance scales) in tests of the gravitational $1/r^2$ law. Suppose, for example, that $\epsilon \approx 0.01|q_V/\mu|$ and $q_V=B$. The laboratory and astronomical $1/r^2$ tests summarized in Ref. 20 supplemented by recent geophysical results[21,22] set bounds on g_S^2 that lead to the constraints on the gravivector acceleration of

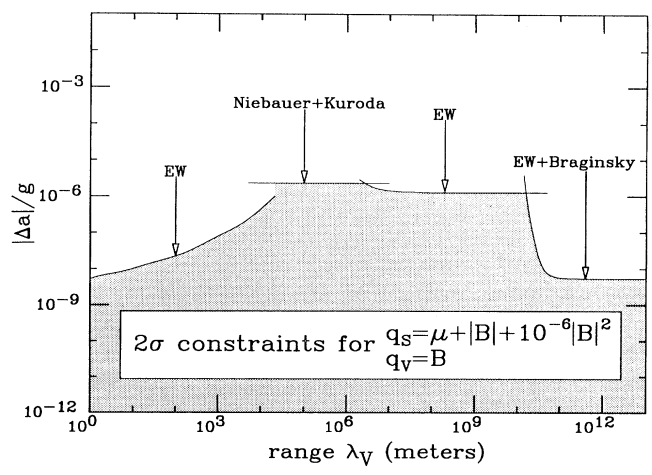

FIG. 3. Constraints on the gravivector acceleration of antineutrons, antihydrogen, and electrically shielded antiprotons for the case where $q_V=B$ and $q_S=|B|+\delta|B|^2$ with $\delta=10^{-6}$. Each constraint was obtained from two equivalence-principle results, by solving for $g_V^2 I_V$ the two equations relating Δa to $g_S^2 I_S$ and $g_V^2 I_V$.

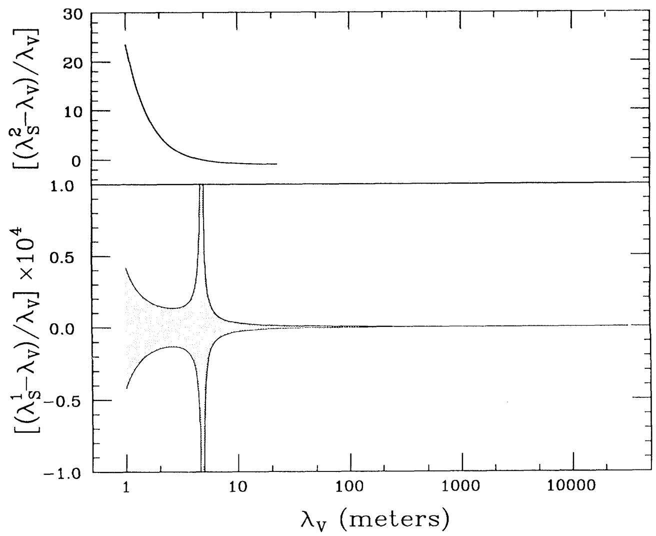

FIG. 4. Constraints from the results of Ref. 9 on the fractional difference of the ranges λ_S and λ_V of the graviscalar and gravivector interactions. We assume that the scalar interaction has gravitational strength, i.e., $g_S^2/4\pi = Gm_p^2$, where G is the Newtonian gravitational constant. Two solutions (denoted by λ_S^1 and λ_S^2) are consistent with the observed null effect. The 1σ regions consistent with the experimental results are shaded; the allowed region for solution 2 is much smaller than the width of the line.

antiprotons shown in Fig. 2.

(3) q_S is a strong function of $|B|/\mu$ and/or $|L|/\mu$. In this regime the graviscalar interaction is highly composition dependent, and q_S cannot be approximated as a linear function of $|B|$ and $|L|$. Suppose, for example, that $q_V = B$ and $q_S \approx |B| + \delta |B|^2$. Even a very small value of δ will prevent cancellation of the graviscalar and gravivector accelerations for a range of materials. If $\delta = 10^{-6}$, the EP results[9-12] (where B ranges from 9 to 238) yield the stringent constraints on the gravivector acceleration of antimatter shown in Fig. 3.

Additional strong constraints on opposing graviscalar and gravivector forces arise from an independent approach. We have pointed out[23] that at the Eöt-Wash experimental site the *direction* of a Yukawa force is a strong function of its range. Thus two opposing forces with ranges $\lambda \ll r_{\text{Earth}}$ can cancel only if they have essentially identical ranges as well as identical strengths. As shown in Fig. 4, our recent data[9] are consistent with scalar and vector interactions of gravitational strength only if λ_S and λ_V coincide to a fractional accuracy that is typically better than 1 part in 10^5 *and* if the ratio g_S^2/g_V^2 has a special value (determined by the scalar and vector charges of the materials involved) that is typically constrained to 1 part in 10^6.

In summary, we have shown that equivalence-principle and inverse-square-law experiments using ordinary matter probe the gravivector acceleration of antimatter in the same way as do direct measurements of antimatter in free fall, and that these ordinary-matter experiments set upper limits on the predicted gravivector acceleration of antimatter that lie well below those expected from the present generation of direct antimatter experiments. There is no evidence for unusual gravitational behavior of antimatter, or for "quantum-gravity-inspired" models which postulate the existence of low-mass spin-0 and spin-1 partners of the graviton.

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[(a)]Present address: Center for Particle Astrophysics, University of California, Berkeley, CA 94720.

[1]J. Scherk, in *Unification of Fundamental Particle Interactions,* edited by S. Ferrara, S. Ellis, and P. Nieuwenhuizen, Ettore Majorana International Science Series Vol. 7 (Plenum, New York, 1980), p. 381; Phys. Lett. **85B**, 265 (1979).

[2]K. I. Macrae and R. J. Riegert, Nucl. Phys. **B224**, 513 (1984).

[3]T. Goldman, R. J. Hughes, and M. M. Nieto, Phys. Lett. B **171**, 217 (1986).

[4]Strictly speaking, any field theory with positive semidefinite energy. Theories that do not have this property suffer from unphysical instabilities.

[5]F. C. Witteborn and W. M. Fairbank, Phys. Rev. Lett. **19**, 1049 (1967); Nature (London) **220**, 436 (1968).

[6]G. Gabrielse, Hyperfine Interact. **44**, 349 (1988).

[7]M. L. Good, Phys. Rev. **121**, 311 (1961).

[8]I. R. Kenyon, Phys. Lett. B **237**, 274 (1990).

[9]B. R. Heckel *et al.*, Phys. Rev. Lett. **63**, 2705 (1989).

[10]T. M. Niebauer, M. P. McHugh, and J. R. Faller, Phys. Rev. Lett. **59**, 609 (1987).

[11]K. Kuroda and N. Mio, Phys. Rev. Lett. **62**, 1941 (1989).

[12]V. B. Braginsky and V. I. Panov, Zh. Eksp. Teor. Fiz. **61**, 873 (1971) [Sov. Phys. JETP **34**, 463 (1972)].

[13]P. Morrison, Am. J. Phys. **26**, 358 (1958).

[14]L. I. Schiff, Proc. Natl. Acad. Sci. U.S.A. **45**, 69 (1959).

[15]L. I. Schiff and M. V. Barnhill, Phys. Rev. **151**, 1067 (1966).

[16]Antimatter experiments with charged particles are also affected by a graviscalar force. When one compares forces on antiprotons and electrons to eliminate electrical effects,

$$\mathbf{F}_{\bar{p}} - \mathbf{F}_e = (M-m)\mathbf{g} + (r_p - r_e)\mathbf{S} - (q_p + q_e)\mathbf{V},$$

graviscalar-gravivector cancellation could occur (r and $\mathbf{S}$ are the graviscalar charge and field, respectively).

[17]C. H. Brans and R. H. Dicke, Phys. Rev. **124**, 925 (1961).

[18]F. D. Stacey, G. J. Tuck, and G. I. Moore, Phys. Rev. D **36**, 2374 (1987).

[19]R. D. Peccei, J. Sola, and C. Wetterich, Phys. Lett. B **195**, 183 (1987).

[20]C. Talmadge *et al.*, Phys. Rev. Lett. **61**, 1159 (1988).

[21]J. Thomas *et al.*, Phys. Rev. Lett. **63**, 1902 (1989).

[22]C. Jekeli, D. H. Eckhardt, and A. J. Romaides, Phys. Rev. Lett. **64**, 1204 (1990).

[23]C. W. Stubbs, E. G. Adelberger, and E. C. Gregory, Phys. Rev. Lett. **61**, 2409 (1988).