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GRAVITATIONAL PROPERTIES OF ANTIMATTER

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Quantum gravity is at the forefront of modern particle physics, yet there are no direct tests, for antimatter, of even the principle of equivalence. We note that modern descriptions of gravity, such as fibre bundles and higher dimensional spacetimes, allow violations of the commonly stated form of the principle of equivalence, and of CPT. We review both indirect arguments and experimental tests of the expected gravitational properties of CPT-conjugate states. We conclude that a direct experimental test of the gravitational properties of antimatter, at the 1% (or better) level, would be of great value. We identify some experimental reasons which make the antiproton a prime candidate for this test, and we strongly urge that such an experiment be done at LEAR.

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I. INTRODUCTION

The advent of grand unification has brought quantum gravity to the forefront of modern particle physics theory.¹⁾

But in fact, only semi-classical gravity has any experimental basis at all. Classical gravity rests on the Eötvös-Dicke^{2,3)} tests of the Principle of Equivalence, and the Parametrized-Post-Newtonian tests consisting of the advance of the perihelion of Mercury,⁴⁾ the deflection of starlight by the Sun,⁵⁾ and the Pound-Rebka red-shift experiment.⁶⁾ The quantum effect of the classical gravitational potential has been seen in neutron interferometer experiments as a phase shift.⁷⁾

Further, there have been no direct tests of the gravitational properties of antimatter. Measuring the fall of antineutrons, either directly, or by interferometric techniques, is extremely difficult due to the large annihilation cross section. Measuring charged antiparticles would seem even more difficult due to the need to screen very small stray electric fields. Although Witteborn and Fairbank succeeded in measuring the gravitational acceleration of electrons to 10% in a shielded drift tube,⁸⁾ they could not complete their attempt to do this experiment with positrons, due to problems with the sources available.

II. STANDARD THEORETICAL ARGUMENTS

Standard theoretical arguments in quantum field theory predict that the gravitational properties of antimatter are identical to those of matter.⁹⁾ The critical elements of the arguments are CPT symmetry, so that a field theory may be constructed, and that the gravitational interaction is due to the exchange of spin-2 bosons (with possibly a small spin-0 Brans-Dicke component). The coupling of a particle and of its CPT-conjugate (antiparticle) state to gravity then cannot change sign, as it depends on even powers of the components of the (anti)-particle four-momentum.

Be this as it may, we believe that these arguments beg the question. In a 1982 Physics Letter,¹⁰⁾ which reviewed these arguments, we proposed a "theorists' experiment", using antiprotons, to provide an unambiguous test.

There are many examples of the value of unambiguous tests of "known" fundamental principles. Most recently, we have seen elegant experimental tests, by Aspect, of quantum mechanics using Bell's inequalities, even though the result was "known". Similarly, Dicke has said³⁾: "It is clear...that if one believes that general relativity is established beyond question by its elegance, beauty,

and the three famous experimental checks, then the Eötvös experiment has no point, for its null result can be derived from theory. However, if gravitational theory is to be based on experiment..." We believe that "gravitational acceleration of antimatter" may be substituted for "Eötvös" without affecting the philosophical content of the comment.

In fact, modern theories of gravity do not even require universality of the simple form of the principle of equivalence, namely "inertial mass = gravitational mass". In fibre bundle theories, the action functional for gravity usually appears as a four-dimensional integral over space of a density composed of the product of a dimensional constant (derived from Newton's constant) and the scalar curvature of space-time. However, it may also appear as an integral over the scalar product of a generalized (to include the group degrees of freedom) four-index curvature tensor with itself. In such systems, a non-trivial torsion appears in the space-time metric, and the corresponding gauge field is a curvature tensor with one index in the group space, and one in the space-time. Furthermore, these systems necessarily include degrees of freedom for which the exchange of this gauge boson produces an interaction amplitude of exactly the same strength as that due to graviton exchange, but with opposite sign. Thus, for these special degrees of freedom, at the tree level, their gravitational mass is identically zero, independent of their inertial mass. For a more complete description, see the series of papers by Macrae.¹¹⁾

IV. POSSIBLE VIOLATIONS OF THE PRINCIPLE OF EQUIVALENCE

Fibre Bundle theories thus allow violation of the simple form of the principle of equivalence even when CPT is an exact symmetry. But must CPT be unbroken? We were reminded by Lowell Brown, in a discussion at Los Alamos, that the CPT theorem has only been proven in locally flat space-times. Yet the higher-dimensional gravitational theories that arise naturally from consideration of local supersymmetry require compactification, and hence essential curvature, in the extra dimensions. (The more recent suggestions of gravitational theories based on quantum strings exacerbate the problem; they are defined in 26 dimensions!) It is clear that such dimensional reduction or compactification may introduce violations of CPT symmetry.

It is not unreasonable, then, to speculate that CPT-violation may even be maximal in gravitational interactions, as parity violation is in the weak inter-

actions. That is, we may only think CPT is a good symmetry because the gravitational effects which violate it are swamped in the strong and electroweak interactions which we do observe. Such a violation may even be necessary: Banks¹²⁾ has recently considered the utility of a T-violation which also violates CPT, in order to define the "wavefunction of the Universe" within the context of inflationary Universe scenarios.

A simple, mechanical model may give some insight into CPT-violation due to dimensional reduction. Consider a long, thin tube, where moving along the length of the tube corresponds to moving in ordinary space-time. Moving transversely to this, around the tube, corresponds to motion in the extra, compactified dimension(s). A (two-dimensional) vector field in the higher dimensional space-time of constant magnitude, and oriented parallel to the length of the tube, appears in the ordinary (one-dimensional) space-time as a constant scalar field value; i.e., a vacuum field value with no physical meaning. Now consider a positive helicity particle moving along the length of the tube, and its CPT-conjugate state (which is an antiparticle) moving in the same direction but with opposite helicity. If there is a spin interaction with the (two-dimensional) vector field, it will change the antiparticle energy oppositely to that for the particle. In the ordinary space-time, we see what appears to be a violation of CPT-invariance.

Of course, we may well expect the effect to be very small, say on the order of the particle mass divided by the Planck scale of the compactified dimensions. An effect suppressed by 19 orders of magnitude or so would be very difficult to see. However, theory can only say that CPT-violation is indeed conceivable, and therefore, gravitational and inertial masses need not be identical. The actual size, and the particular true theory, can only be determined experimentally. It follows that the most direct and unambiguous test should be made. We believe this to be a measurement of the gravitational properties of the antiproton. We continue to be enthralled by the possibility that it is the gravitational interaction which is maximally CPT-violating.

IV. PREDICTIONS FROM GRAND UNIFICATION

One of the more popular grand unified theories is the SU(5) model.¹³⁾ In this theory, the positron and electron-antineutrino are symmetry partners to the right chiral down quark, in the five-dimensional representation. Thus, we may say that the positron is "matter" as that is composed primarily of up and down quarks. The test of the gravitational acceleration of electrons by

Witteborn and Fairbank,⁸⁾ in the SU(5) theory, is then a 10% measurement of the gravitational properties of antimatter! Unfortunately, the SU(5) theory also predicts that protons decay into positrons and neutral pions with a lifetime less than about 10^{32} years,¹⁴⁾ and this conflicts with experimental results.¹⁵⁾ Extensions of SU(5) can save it, but we cannot draw our conclusions until proton decay is seen and confirmed to be consistent with these extensions.

There are many alternative grand unified theories. A class due to Pati and Salam¹⁶⁾ consists of products of four factors of SU(2n), where $n > 2$. In these models, the electron is the partner of the down quark, and so the Witteborn-Fairbank experiment cannot be said to address the gravitational properties of antimatter, if one of these models is found to be correct. Thus, although it seemed promising a few years ago, grand unification does not help us draw a conclusion on these properties without further experiment.

V. LACK OF INDIRECT EXPERIMENTAL EVIDENCE

Given the lack of theoretical guidance noted above, we now ask if there are any indirect experimental arguments based on fundamental principles which can say anything about the gravitational acceleration on antimatter. The surprising answer which we give is, "No."

a) K^0 Mesons

A first argument for the equality of g and $\bar{g}$ is an ingenious one due to Good.¹⁷⁾ Much to his credit, he thought of it even before the violation of CP was discovered.

Good observed that since the K_L is a linear superposition of the K^0 and $\bar{K}^0$, in an (explicitly assumed) absolute gravitational potential the energy difference between the K^0 and $\bar{K}^0$ should therefore be $2M_K \phi_G$. The K_L would instantaneously regenerate some K_S , just as it does going through matter. Since it did not (remember, CP violation had not been seen), Good reasoned that this excluded $g \neq \bar{g}$.

However, in the light of modern gauge theories, we believe that an absolute potential is not valid; it is the potential difference that is important (Think of a photon creating an e^+e^- pair in the middle of a condenser. The two particles are not instantaneously separated, but must evolve before the potential difference is realized.) Indeed (as Good himself recognized, we emphasize), an absolute potential would lead to the quandary of whether the earth's, sun's, galaxy's, local group's, or universe's potential is the correct

one to use. The last is naively of the order of the rest mass of any particle created and was one of the intuitive bases of the old continuous creation of matter cosmology.

b) CPT

If CPT is conserved, then quantum field theory says that an antiparticle must have the same mass, lifetime, and magnetic moment (but with opposite sign) as the corresponding particle. In the case of the antiproton, its mass is known only to $[m(p) - m(\bar{p})]/m(p) = (7 \pm 4) \times 10^{-5}$. Thus, we think it is very important to improve this number. We encourage the efforts of the group involving Professor Klapisch and the new proposal by Gabrielse which will be discussed at this meeting.

The problem for us, however, is how to quantitatively relate a possible CPT violation with a violation of the principle of equivalence. This point has been magnificently elucidated by Tanner in his talk at this Workshop. Tanner pointed out that limits on the masses of the K^0 and $\bar{K}^0$ should not be considered to be evidence for CPT conservation to order 10^{-14} to 10^{-18} (the variation in numbers involves more-or-less proved assumptions). Rather, such a conservation must be considered on the scale of the interaction involved. Thus, the critical number here is the weak scale, or $[m(K^0) - m(\bar{K}^0)]/[m(K_L) - m(K_S)] \leq 1.3 \times 10^{-2}$. This is not a strongly verified conservation principle.

As already mentioned, the similar point here is, "Even if gravity violates CPT maximally, how could you obtain a measurable effect?" It might well be beyond measure.

c) The Eötvös-Dicke Experiments and Schiff's Argument

The classic experiments of Eötvös²⁾ and Dicke³⁾ showed that the gravitational mass (m_g) differs from the inertial mass (m_I) by less than a part in 10^{11} . (The essence of the experiment was that equal "weights" of different materials on a balance do not rotate, as they would if their inertial masses were different on the rotating earth.)

Now, in the field of any atom (in particular hydrogen) there is a field theory shift of energies due to the "vacuum polarization" or "Uehling potential". (See Fig. 1.) This contributes a small amount of the total Lamb shift of 1058 Mhz between the $2s(1/2)$ and $2p(1/2)$ levels. Now, the size of the vacuum polarization is only $\Delta E = -27 \text{ Mhz} = -1.1 \times 10^{-7} \text{ eV} = -1.1 \times 10^{-16} \text{ GeV}$, or an effect of one part in 10^{16} since a proton has a rest mass of about $1 \text{ GeV}/c^2$. For heavier atoms, the fractional effect is still of this same order of magnitude.

Fig. 1. The vacuum polarization diagram in QED.

Fig. 2. The vacuum polarization diagram in QCD.

Schiff¹⁸⁾ argued that there were contributions of antimatter to the total mass of matter on the order of electron volts, and hence $g = -\bar{g}$ was ruled out by the Eötvös experiments. However, this amount is comparable to the contribution due to binding energy (virtual photons), whereas the vacuum polarization from which the antimatter (positrons) arises is a higher order QED correction to the binding energy, and so should be much smaller. In fact, although Schiff was careful to pick a finite calculation of this contribution, he did not subject it to a (finite) renormalization. Even when higher order corrections are finite, quantum field theory is now understood to require such a renormalization. When this is done, the antimatter contribution is indeed found to be negligibly small on the scale of Dicke's test.

d) QCD Uehling Potential

However, there is a new question as to whether the analogue of the Uehling potential in QCD produces a discernible effect. (See Fig. 2.) A rough guess is that the antimatter contribution might be of order 10^4 larger because of the ratio $(\alpha_s/\alpha)^2$ where α_s is the strong coupling constant. However, that is only a guess. There are possible Uehling effects of the confining part of the QCD

potential, larger Q^2 (squared four-momentum transfer), the fact that α_g itself is a function of Q^2 , and that much of the energy may be in the bosonic gluons. To answer this question one must do a very serious calculation.

VI. LACK OF DIRECT EXPERIMENTAL EVIDENCE

After all this, we must ask if direct experiments have said anything. This time the answer is a little better, but not much.

a) Massless Bosons (Light)

Light is a massless, spin 1 (self-conjugate) boson. One polarization is the antiparticle of the oppositely polarized particle. Therefore, if light behaved abnormally, one polarization would rise in a gravitational field and the other would fall.

This issue was settled in the eclipse of 29 May 1919, which was the eclipse that performed one of the classical tests of general relativity.⁵⁾ By comparing field plates without the sun with field plates with the sun, the nearby stars had their light deflected by the predicted angle of

$$\theta = \frac{4M_0 G}{Rc^2} \frac{1}{2} [1 + \gamma] = 1.75'' [R_0/R]$$

Only one deflection occurred, not pairs for opposite polarizations. Light was further tested in the Pound-Rebka experiments.⁶⁾ As light fell in the Jefferson Physics building tower at Harvard, its frequency changed as

$$\nu = \nu_0 [1 + gH/c^2]$$

with an accuracy of $[0.9970 \pm 0.0076]$. The correction term did not change sign for different polarizations.

Light remains the only boson, massless or massive, whose gravitational properties have been tested.

b) Massive, Chargeless, Fermions (Neutrons)

Every time you drop a ball you test the bulk properties of chargeless, fermionic matter. But a single fermion is a different case, especially for a charged fermion since stray electric fields will overwhelm the gravitational effects on a charged particle. As an example, note that the ratio of the strengths of the gravitational force to electric forces on an electron can be parametrized by the quantity $[m_e g/e] = 5.6 \times 10^{-11}$ V/meter.

Thus, it is chargeless neutrons which provide the easiest test. The idea of McReynolds¹⁹⁾ as updated by Dabbs, et al.²⁰⁾ was simply to let thermal neutrons come out of a reactor, be collimated by a Bragg crystal, and then fall over a path of 180 m. The result²⁰⁾ was that the local gravitational acceleration on neutrons is $(973.1 \pm 7.4 \text{ cm/s}^2)$. For the antineutrons you have all kinds of problems from getting a thermal source to annihilation effects. Ted Kalogeropoulos has thought a great deal about this, and we suggest that interested people should consult him.

However, more importantly, neutrons have allowed us to see that gravity is a quantum-mechanical potential for massive fermionic fields. This was shown in the C.G.W. experiment.⁷⁾ These people split up a neutron beam in an interferometer. One half of the beam (A) was raised higher than the other (B), transversing a higher gravitational potential. Meanwhile, the other half (B) travelled horizontally in the lower potential and then was raised to interfere with beam A. (The paths of the two beams formed a parallelogram.) As the plane of the parallelogram was rotated, the fringes of the interfering beams changed. This meant that gravity affected the two quantum-mechanical waves in the two paths as expected.

Therefore, even though we do not have a quantum theory of gravity, we have a semi-classical theory of gravity. The effect of gravity appears as a classical potential which affects the quantum-mechanical particles (neutrons). This is analogous to the old semi-classical theory of radiation, where the classical electromagnetic field affected the quantum-mechanical particles (electrons and protons).

c) Charged Fermion (Electrons)

The only successful measurement of gravity on charged particles was the experiment of Witteborn and Fairbank⁸⁾ on electrons. This experiment was delightfully simple in concept, although excruciatingly difficult in implementation. Simply stated, low energy electrons were sent up a shielded drift-tube (Fig. 3) to see if they "slowed down."

But even the "slowing down" was difficult to understand. Schiff and Barnhill²¹⁾ had observed that because electrons in a metal should sag under gravity, this sagging would produce a net electric field cancelling the gravitational field felt by the drifting electrons. Thus, electrons should travel up without slowing down. Indeed, the measured force on the electron was 0.09 %, i.e., a 10% experiment.

In general, the effective gravitational constant in this situation for a particle of mass M and charge Q should be

$$g_{\text{eff}} = g \left[1 - \frac{m_e}{M} \frac{Q}{e} \right] .$$

Thus, for a positron the measured constant would be $2g$! As stated, an attempt was made by Witteborn and Fairbank to measure this, but a sufficiently low energy source of positrons was not available. Note, however, that because of the small mass ratio $m_e/m(\bar{p})$, the predicted effect on antiprotons of the Schiff-Barnhill effect would be negligible, and could be calibrated with protons and negative hydrogen ions.

VII. THE PROPOSAL TO MEASURE THE GRAVITATIONAL ACCELERATION ON ANTIPROTONS

Because of all this, we¹⁰⁾ proposed a "theorists' experiment" to measure the gravitational acceleration on antiprotons. The idea was simple: extract low energy antiprotons from LEAR, decelerate them, and then send them up a drift tube.

Well, now our colleagues have turned the idea into an "experimentalists' experiment". In addition to the Los Alamos proposal which is being outlined at this workshop by Billen and Hynes, there are the ideas of Gastaldi and of Torrelli (who incidentally deserves much credit for having thought about these types of ideas for so long).

The comparison of the gravitational acceleration of antiprotons and protons is in principle the best and clearest experimental test for antimatter. It has no real theoretical bias.

An experiment to measure $g(\bar{p})$ would be a classic! An experiment accurate to 10^{-2} or 10^{-3} would be even more significant since violations of great principles seem to appear in this way.

This experiment would be one for the textbooks! It would be like the Eötvös-Dicke experiment, the Pound-Rebka experiment, the experiments to measure rotation of 4π , the C.O.W. experiment, the Aspect experiments on Bell's inequalities. All the above experiments got exactly the expected results. Yet they were all such beautiful and clear verifications of our physical understanding that they are classics. They are experiments that go into the text books.

Our question is "To that list will there be added the LEAR experiment which measured $g(\bar{p})$?" As theorists we can only say we hope the answer is, "Yes." We hope that the LEAR community will be convinced to do this experiment and, of course, we hope that Los Alamos will be able to play a part in such an experiment.

Thank you very much.

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Fig. 3. The Waterborn-Fairbank drift tube.