Los Alamos

Los Alamos National Laboratory
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Essays on Gravitation
Mr. George M. Rideout, President
Gravity Research Foundation
Fifty-Eight Middle Street
Gloucester, Mass. 01930

Dear Mr. Rideout;

Enclosed you will find three copies of the essay "The Gravitational Acceleration of Antiprotons," along with three extra copies of the title page containing a summary.

T. Goldman, M. V. Hynes, and myself submit this for the 1985 Essays on Gravitation.

Sincerely yours,

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THE GRAVITATIONAL ACCELERATION OF ANTIPROTONS

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SUMMARY

We review the theoretical arguments and experimental evidence (both direct and indirect) for the conventional view that the gravitational acceleration of antimatter must be the same as that of matter. We find there is no compelling support for such a belief. Therefore, we propose to measure the gravitational acceleration of antiprotons using a beam extracted from the Low Energy Antiproton Ring (LEAR) at CERN.

The two great revolutions of modern physics, relativistic quantum field theory and general relativity, have never been successfully united. Theoretically we may just have the barest beginning glimmer of how to proceed. Experimental progress has been made to the point of showing with an interferometer that Newtonian gravity influences the quantum mechnical (not yet field theoretic) wave functions of neutrons in a gravitational field.[1] Also, attempts have been made to have gravity induce the AC Josephson effect in liquid helium.[2] However, these effects are Newtonian, not Einsteinian. Further, even for proposed studies of Einsteinian effects, one deals only with quantum mechanics (fixed particle number) not quantum field theory.[3]

The most obvious reason that these two areas are difficult to connect experimentally is the extremely weak nature of the gravitational force. The effective dimensionless coupling constants are: ~ 1 for the strong interaction, $\sim 10^{-2}$ for the electromagnetic interaction, $\sim 10^{-7}$ for the weak interaction, and $\sim 10^{-40}$ for gravity.

In essence this is also one important reason why theoretical attempts to unite these two areas have been so difficult; they have lacked experimental guidance. The ideas that have allowed the electroweak theory, and the QCD candidate theory for the strong interactions, to be extended to discussion of unification of the first three forces, have been aided by experiments that either had already been done or else were sufficiently feasible to soon provide tests of the predictions. That certainly does not seem to be the case for a possible unification with gravity. Furthermore, it is not even clear that the two concepts (field theory and general relativity) are theoretically compatible in their present formulations. Thus, any test which can shed light simultaneously in these areas is of extreme importance.

Coming to the additional complication of antimatter, standard theoretical arguments in quantum field theory predict that the gravitational properties of antimatter are identical to those of matter.[4,5] The critical elements of these 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, by the assumption of simple CPT invariance. Modern field theories of supergravity and higher dimensional spacetimes do allow the construction of CPT-violating theories of gravity in four spacetime dimensions. Of course, if CPT is violated, then the principle of equivalence may not be valid. In fact, even in some CPT-conserving theories, there are degrees of freedom for which the simple form of the principle of equivalence fails to hold.

Indirect arguments do not rule out the possibility that g for an antiparticle does not equal g for a particle. The proposal[6] that such an inequality would lead K_L's to spontaneously transform into K_S's was based on the (admitted) assumption that there is an absolute gravitational potential. Such a view is not consistent with that of modern gauge theories.[7] The proposal,[8] that the presence of virtual e^+e^- pairs in atoms (due to vacuum polarization) rules out $g(e^+) \neq g(e^-)$ because of the Eötvös experiments,[9] is not correct. Even with the Dicke experiment[10] this is not true, because the vacuum polarization effect is only 27 Mhz = 1.1×10^{-16} GeV, which is five orders of magnitude away from the accuracy of the Dicke experiment.

Furthermore, except for comparing the two polarizations of massless photons, there have been no direct tests of the gravitational properties of antimatter. Measuring the fall of antineutrons, either directly or by interferometric techniques, would be 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. Nonetheless, Witteborn and Fairbank did succeed in measuring the gravitational acceleration of electrons to 10% in a cold, shielding, drift tube.[11] However, they could not complete their attempt to do this experiment with positrons, due to problems with the available sources.

It is therefore appropriate to speculate that $g(\bar{p}) \neq g(p)$ and that CPT-violation may even be maximal in gravitational interactions, as parity violation is in the weak interactions. That is, we may only think CPT is a good symmetry because the gravitational effects which violate it are swamped by the dominant strong and electroweak interactions.[12] Clearly, the simple form of the principle of equivalence would also fail.

Because of earlier versions of the above arguments, in 1982 Goldman and Nieto[5] proposed that the gravitational acceleration of antiprotons be measured at LEAR (the Low Energy Antiproton Ring at CERN) by decelerating them and sending them up a drift tube. The advantage of using antiprotons over positrons is that the main systematic bias is reduced by a factor of $m(\bar{p})/m(e) \simeq 2{,}000$. This bias is due to the electrons in the metal drift tube sagging under gravity until they produce an equal and opposite electric force. Thus the measured gravitational acceleration will be

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

This is zero for electrons (which Witteborn and Fairbank measured to 10%), 2g for positrons, but approximately g with calculable and in principle measurable differences for protons, antiprotons,and negative hydrogen ions. This last would be of immense utility in calibrating an experimental apparatus, because it has the same charge as and very similar mass to the antiproton.

Recently Hynes initiated development of a collaboration[13] to perform this experiment.[14] The experimental plan is to take the output of LEAR at its lowest energy, 2-5 MeV, and decelerate it using a radio frequency quadrupole structure and associated beam line elements.[15] The antiprotons would emerge at 20 keV. They would then be stored and cooled to very low temperatures in an ion trap.[14] Finally the antiprotons would be launched up a drift-tube, as Witteborn and Fairbank did in measuring the gravitational acceleration on electrons.

The comparison of the gravitational acceleration on antiprotons and protons is in principle the best and clearest experimental test for antimatter. It has <u>no</u> real systematic or theoretical bias. A measurement at the 10^{-2} or 10^{-3} level would clearly be of great significance.

There are certain experiments which have obtained exactly the results expected, and thus have solidified our understanding of Nature.

Examples are the Eötvös-Dicke experiments, the Pound-Rebka experiment, the gravitationally affected neutron interferometer experiment, Aspect's experiments on Bell's Inequalities, and the rotation of 4π experiments. These experiments are all classics.

We all expect that an experiment to measure the gravitational acceleration on antiprotons will yield the result: $g(\bar{p}) = g(p)$. Each of us has his own private dreams or nightmares about a different result. But whatever the outcome, such an experiment is sure to be a classic.

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12. Indeed, as noted above, there are even suggestions in modern research that such things can be accomplished by dimensional reduction or CPT violations in curved space-time.
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