

ON THE GRAVITATIONAL INTERACTION OF MATTER AND ANTIMATTER

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A gravitational interaction between matter and antimatter is considered that would preserve symmetry between the signs of electric charge, and would allow this symmetry also to apply to the large scale distributions of matter in the universe. A repulsion between unlike types of matter is then required to allow a sorting into galaxies of one type or the other to take place, and such sorting is essential to avoid wholesale annihilation. While this law of repulsion would violate the principle of equivalence and the principle of covariance, it would do so only in circumstances where both types of matter are significantly involved. No experiment has yet been carried out where this is the case.



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The principle of Equivalence between a local gravitational field and a uniform acceleration has been made the axiomatic foundation of the General Theory of Relativity. The relation of this principle to the strict proportionality between inertial and gravitational mass:  $M_i/M_g = \text{const.}$  is evident. Empirical verification of this relation has been carried out to a precision of about one part per million for the various components of mass: nucleon rest mass, electron rest mass, and binding energy (nuclear and atomic). The verified consequences of the General Theory of Relativity rest essentially upon the Principle of Equivalence, and this in turn upon the stringent tests, in experiments of the Eötvös type.

It is appropriate to ask, especially now in view of the non-conservation of parity, whether such a close empirical agreement is indeed the mark of a universal law, or simply a close approximation in the available context of the experiment. One can note that the experiment has been carried out in an environment that may be highly special. Antimatter which, according to our present understanding of charge conjugation, is represented on an equal footing in the physical laws, is excluded to a very high precision both from the experimental apparatus, and from any of the masses that exert significant gravitational forces in its neighborhood, (such as the Earth, the Sun the galaxy). The relative error allowed by the

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experiment is far larger than the proportion of antimatter that may be effective. ~~It~~ Is the accuracy with which the inertial mass equals the gravitational mass perhaps conditioned by the accuracy with which antimatter is excluded from the experiment?

Cosmological enquiry leads one to pursue such a possibility.

It is often assumed that all the matter in the universe is of the same type. Whilst it is legitimate to conclude that normal galaxies including ours could not be made of a mixture of matter and antimatter, for reasons of violent annihilation processes that would be occurring, such an argument cannot be used for the universe as a whole. No present observational evidence can be used to show that galaxies are not of two sorts. Their contact with each other and with the intergalactic gas may be sufficiently slight to avoid gross effects at the boundaries. Gravitational, inertial, and electromagnetic phenomena would be alike in both types of matter, and the astronomical observations could not make the distinction.\* It would be necessary to sample the matter, such as perhaps by the examination of heavy cosmic ray nuclei or the neutrino-flux, or to observe characteristic effects of annihilation processes. Indeed there are some distant objects, of which M37 is the most conspicuous example,

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\* More rigorously it could be argued that the non-conservation of parity would allow the possibility that antimatter could be distinguished electromagnetically, by showing a preference for one or the other screw-sense in some circular polarization. Present theory would make any such effect very small.

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which appear to derive large amounts of energy from yet unknown sources. It is not to be excluded that annihilation processes play a role in such extraordinary phenomena.

If all matter in the universe were in fact of our type only, then this asymmetry would play a major part in cosmological theory. One would then wish to give a reason why those physical processes that gave rise to this matter did not share the symmetry with respect to charge that we now observe in physical laws. But if both types of matter are equally represented so that on a large scale the world is charge-symmetric (and therefore mirror-symmetric), some process must have separated the two types into different galaxies with great precision. This could be thought of as a dynamical feature of the unknown process of creation, as has been suggested elsewhere. Any less postulational approach to cosmology, particularly the steady-state cosmology or almost any version where matter is currently created would imply a presently-valid mechanism of separation. Since the large-scale processes of galactic condensation are probably <sup>caused</sup> by gravitational force, one may attempt to modify the law of universal gravitation in the minimum degree to maintain consistency with other major physical postulates, but enough to guarantee the separation of matter and antimatter. In the next section, we outline the arguments required for consistency, and we present the Newtonian limit of such a theory. In this theory if nucleons and

anti-nucleons mutually repel gravitationally. ii) each kind attracts its own kind, and iii) other forms of energy (electrons, positrons, photons, binding energy) are mutually attracted, in the ordinary way, both to nucleons and to anti-nucleons.

Such a theory requires  $M_g/M_I$  not to be a universal constant, and therefore contradicts the postulational basis of General Relativity. Special Relativity, too, is contradicted, as it is by other gravitational theories. Both of these conflicts lie beyond the present experimental test, but are in principle verifiable. It is at this point that our hypothesis escapes the criticism made by several authors (Peaslee, Bergmann) who deduce from the principle of equivalence and the transformation laws of relativity theories that nucleons and anti-nucleons cannot repel gravitationally.

In such a case there would seem to result no excessive amounts of annihilation radiation during the sorting process even if, as in the steady-state theory, the matter started generally in intergalactic space and condensed from there into galaxies. Very rarely a condensation could possess a sufficiently high peculiar motion to overcome the repulsion and collide with an opposite-type condensation.

Conditions on the Interaction

Let us examine the conditions set on the gravitational interaction of nucleons with anti-nucleons, and of both with energy (electrons, kinetic energy, binding energy, etc.) which is not in nucleon form. Consider an ordinary uniform gravitational field, in which a belt passed over an ideal pair of pulleys permits the work-free motion of two counterweighted pans up and down along the lines of force: a "dumbwaiter." If in one pan we place an atom, and in the other an identical atom, no work is done if the belt carries both pans with their load around a complete turn. But if one atom is excited, it will weigh more than its counterpoise, and fall, releasing energy  $W$ :

$$W = E/c^2 \times \Delta V \tag{1}$$

where  $E$  is the excitation energy,  $\Delta V$ , the potential change =  $g \times$  distance of fall. If now we de-excite it at the bottom, the released quantum may travel out in the field, and be re-absorbed by the counterpoise atom, restoring the initial condition. A cycle has been completed, and the work  $W$  of (1) gained. This is inadmissible, and from this we may conclude that a photon is red-shifted in such a field, so that the emitted photon arrives at the counterpoise position with an energy less than the excitation energy by the amount

$$\Delta E = \frac{E}{c^2} \Delta V, \text{ or } \frac{\Delta E}{E} = \frac{\Delta V}{c^2} \quad (2)$$

This is the ordinary red-shift of Einstein.

Now we repeat this experiment, but in the two pans we place matter of the opposite charge to that causing the uniform field. We assume now a repulsion, not an attraction. The argument goes exactly as before, except that for a red shift we will find a violet shift required for the photon.

So far we have assumed that  $|m_0| = |m_1|$ , only the sign of  $m_0$  changing between matter and antimatter. Now we can test this assumption by placing a pair, one atom and one anti-atom, in a single pan. The dumbwaiter is then in neutral equilibrium. But if, say, the atom is excited, it will be heavier, and the pan will fall. De-excite it, transferring the energy to the anti-atom. Now it will have a higher value of its mass, assuming that  $|m_0| = |m_1|$ . But it is repelled by the ordinary field. Then the pan will rise. After the rise, again transfer the excitation to the atom, and the cycle is complete, but with net work done. We take it that any process that can be made into a cyclic one that generates energy indefinitely is forbidden, and we have thus demonstrated that we cannot assign the relation  $|m_0| = |m_1|$  if we assume that there is gravitational repulsion between charge conjugate nucleons.

But we can still maintain consistency and charge-symmetry.

We need to assume that the gravitational mass divides into two kinds: one the nucleon mass, one, any other form of mass or energy. The nucleon mass would be a "gravitational charge" that can be of either sign and thus be either repelled or attracted by other nucleon or anti-nucleon mass. The remaining mass must be attracted by ordinary matter, as experiment shows; for symmetry it must also be attracted by anti-matter. The nucleon "gravitational charge" would be subject to a conservation law similar to the electric charge, which would agree well with the observed conservation of nucleons. A non-relativistic scheme of attraction and repulsion of this sort leads to overall repulsion of charge-conjugate matter, but to complete equivalence of inertial and gravitational mass as long as only one kind of matter is investigated.

In the present scheme the products of nucleon-anti-nucleon annihilation would show a shift\* different from the shift of products of other radiative or decay processes. A pair of observers in the traditional rising elevator would be able to distinguish between a gravitational field and a uniform acceleration. The observer using nucleons would see, say, his matter falling; his anti-observer, the opposite. It is, moreover, true that a single observer could select a preferred inertial frame by purely mechanical observations. He would choose that frame velocity in the extra-galactic space at which the difference

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\* zero shift if no electromagnetic mass were involved.



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between the free fall of particle and anti-particle was a maximum; all others would imply a higher velocity with respect to the mass distributions in the universe. In general, the division, essential to the theory, between rest mass and binding energy  $E_B$  cannot be a covariant one; this expresses itself in allowing the gravitational choice among inertial frames. It is clear that all these effects are measurable in principle; in practice, there is so little anti-matter around that, even were the nearest galaxy to our own made of pure anti-matter, its anti-gravitational effects would affect the relation  $m_1 \approx m_0$  by less than a part in  $10^{15}$ .

The intrinsic perfection of the General Theory of Relativity cannot easily be dismissed as meaningless accident. In the present case it would represent the valid gravitational theory on all but the largest scale. But on the largest scale when both types of matter are represented in different galaxies, a theory of greater generality would have to apply. It should be noted that on this scale the actual motion of matter defines a preferred frame at each point, for example the frame from which the motions of all galaxies appear the most symmetric. It would not be inappropriate if in this more general theory the requirement of covariance disappeared, making it unnecessary to introduce a postulate like that of Weil to account for the actual state of motion of the matter.

We conclude that the anti-gravitational forces suggested by the cosmological arguments would be real without having yet manifested themselves in any experiment. We would argue strongly that the apparent success of theories, like general relativity, in which no such forces can occur, ought not to be allowed to prevent the experimental and astronomical inquiries, which alone can settle the problem of whether universal gravitation is genuine, or merely a consequence of the near-universal prevalence of nucleons in our effective world of observation. It is possible that anti-gravity exists and that it could be demonstrated on Earth. While this would profoundly affect the structure of physics it is not clear that there would need to be any conflict with actual experimental data.

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Short Biographical Sketches:

Phillip Morrison: born in Somerville, New Jersey, 1915. Graduate of the public schools of Pittsburgh, Pa., and received B.S. in physics, Carnegie Institute of Technology, 1936, and Ph.D., University of California at Berkeley, in 1941. Served the Manhattan District, U.S. Engineers, from 1942 to 1946 in Chicago, Los Alamos, the Marianas, and Japan. Since 1946 on the faculty of Cornell University; now Professor of Physics and Nuclear Studies there.

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Thomas Gold: born in Vienna, Austria, 1920. Schooling in Switzerland, M.A. in Mechanical Sciences at Cambridge, England, British Admiralty research on Radar 1943-1946. Fellow of Trinity College, Cambridge; Chief Assistant to British Astronomer Royal 1952-1956. Now Professor of Astronomy at Harvard University.

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