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ANTI-GRAVITY*

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The first suggestion that an undiscovered aspect of gravity might be used for space travel with which I am familiar was made by H.G.Wells. His *First Men in the Moon* used a gravitational *insulator* called Cavourite to surround the space capsule which transported them. Maneuvering was accomplished by opening and closing "shutters" which exposed the gravitating interior to a directional force which depended on the objects in the solar system which were brought into view. The "on-board computer" for the outbound voyage to the moon was Cavour, — the inventor of the substance and designer of the vehicle. That his companion's solo return journey to Earth succeeded was admittedly a matter of extremely good fortune.

I suspect that the Gravity Foundation's prize, offered for scientific essays discussing "gravitational insulators" and related subjects was either directly or indirectly inspired by this story. So far no plausible suggestions have turned up. The analogy is taken from electricity. Electric charges of opposite sign bound to form a neutral matrix are unaffected by electric fields to the extent that polarization of the charges can be neglected, and shield the interior material from external electric fields. For the gravitational analog to exist, there would have to be both gravitic and anti-gravitic "gravitational charges" and some way to form a neutral matrix from them.

The question of whether there are two types of "gravitational charge", and consequently whether some kinds of matter (most simply called "anti-matter") might "fall" UP in situations where ordinary matter falls down is not yet decided. With respect to electric charge, "anti-matter" certainly exists, and has been intensively studied since the discovery of a positron in the cosmic radiation by Anderson in 1932. All the high energy particle accelerators produce particle-antiparticle pairs copiously. The electric charge of each member of such a pair is equal in magnitude but opposite in sign (if one is positive the other is negative) to that of the other member. This is a consequence of a general property of current theories of elementary particles: if the direction of motion of all particles is reversed *and* the description "left" or "right" for all three directions of motion is reversed *and* the

particle-antiparticle description is reversed, the resulting theory makes no experimentally observable prediction that differs from that of the original theory. This is called *CPT invariance* — a mnemonic for Charge reversal, Parity reversal (mirroring, which interchanges left and right) and Time reversal (reversing the direction of velocities). This applies to every known force, EXCEPT gravity.

The idea that anti-gravity might describe anti-matter has been discussed ever since the CPT theory became compelling to theorists. Experimentalists are properly skeptical about the theoretical arguments — which we discuss below — that removed gravity from the list. Bill Fairbank here at Stanford spent a number of years trying to see whether or not positrons (i.e. positive electrons) “fall” up or down. Unfortunately, the experimental problem of constructing conducting tubes smooth enough to shield out external electric fields defeated him. Electric charge clings to rough patches on the interior of such a tube and is not removed by any known technique to the level of accuracy he would have needed to make a measurement.

The experimental question has been reopened recently, thanks to the success of Gabrielse of Harvard in slowing down and capturing *anti-protons*, which are the negative (anti-matter) counterpart of the positive nucleus of the hydrogen atom (proton). Anti-protons are produced at CERN (Centre European de Recherches Nucléaire) outside Geneva for injection into the high energy accelerators which carry out a major portion of their research program. Some years ago a Low Energy Antiproton Ring (LEAR) was constructed to slow down a few of these robbed from the main program to energies of a few million electron volts. This in itself was quite a feat; the related experimental programs produced results of interest to nuclear physicists for several years. But what was needed for the type of experiment in which we are interested was to slow these anti-protons down by another factor of several thousand million without losing them by annihilation with ordinary matter. Gabrielse's team succeeded in doing this and holding them in a high vacuum volume using electric and magnetic fields — a “Penning trap”. They can stay there for weeks without too much loss!

Since the anti-protons go batting back and forth between two interior positions in the Penning trap, they are going slower at the ends than in the middle. Therefore there is more time for gravity to act on them at the ends than in the middle. Consequently, if anti-protons act like ordinary matter, the paths they follow will be higher in the middle than at the ends. The reverse will true if they "fall" up. Unfortunately Gabrielese's magnificent achievement is still not enough for the measurement to be made. The difference in height between the ends and the middles of the paths is sufficiently large to be detected, all other things being equal. But they are not. There is a lot of electric and magnetic activity at the nearby injector to the CERN accelerators, as well as due to LEAR itself; this "noise" defeats current attempts to shield it out, and swamps the signal which would have to be measured. One scheme is to make the trap portable and move it to a "quiet place" where precision experiments are possible. Gabrielese has already moved trapped electrons from LA to Boston in an ordinary moving van, so this is possible. Money and time (he estimates five years, given the money) are all that appear to be needed.

Another team, under Holzscheiter from Los Alamos, is currently on the floor at LEAR. His Penning trap is similar to the Harvard setup, but is followed by a vertical shielded tube similar in concept to Fairbank's. Unfortunately his funds are probably inadequate to complete his task in the year he currently has available. Even if he gets his trap working during this period, he has no confidence that the patch effect which defeated Fairbank is sufficiently under control to make a gravity measurement. His *a priori* advantage is that anti-protons are 1836 times more massive than positrons, but this may not be enough. He has confidence that, eventually, he can measure gravitational effects on mercury ions, which are yet another factor of 200 heavier. And he can use negative hydrogen ions, which have a mass of 1838 compared to the antiproton's 1836, to calibrate his apparatus. Eventually, he should succeed.

A third approach is to capture positrons (electrons with positive charge) in the same trap as the anti-protons and use laser induced transitions to form neutral

anti-hydrogen *atoms*. This was one main topic of discussion at a recent conference in München which I attended. A report appears in the September 25 issue of *Science*, **258**, 1858-1860 (1992). Again the estimate of time to result is the order of five years. Once anti-hydrogen is made in this environment, the measurement is straightforward. The weight of individual hydrogen atoms has already been measured by suspending them in a similar environment using an adjustable magnetic field. The same technique is no more difficult for anti-hydrogen atoms.

We return now to the theoretical situation. The first serious proposal that anti-protons “fall” up which came to my attention was a paper by Scott Starson prepared for, but not presented at, the conference *Physical Interpretations of Relativity Theory, II* held at Imperial College in London during September, 1990. I first met Starson there, and had extensive discussions with him then, which have continued. I had not thought about anti-gravity in the context of the ANPA program prior to this encounter. I was surprised to see that it is indeed possible to cast Bit-String Physics into a form which allows a consistent formulation of a theory of gravitational charge; these charges do indeed reverse between particle and anti-particle, as one would expect from CPT. I reported on this at ANPA WEST 7 in February, 1991 in a joint paper with Starson which appears in the Proceedings. Subsequently I have convinced myself that my theory *predicts* anti-gravity for all forms of anti-matter. Since few members of ANPA agree with me, and no scientist other than Starson that I know of outside of ANPA, I review the theoretical arguments against our prediction.

To begin with, our prediction is in flat contradiction with the equivalence principle (i.e. that there is no way to detect a difference between gravitational and inertial mass) and hence with General Relativity. For many physicists this is already sufficient reason to dismiss anti-gravity out of hand. Only particle theorists and others who believe in CPT invariance will pursue the matter further. But the usual context in which CPT invariance arises is in the second quantized relativistic field theory. In such theories the electromagnetic field has quanta with spin 1 while gravitation has quanta with spin 2. There is a general argument that, although

the force between two particles which exchange spin 1 quanta is repulsive between a pair of particles or a pair of anti-particles, and attractive between a particle antiparticle pair, it is always attractive between *any* two systems which exchange spin 2 quanta.

However, if one looks at the “proof” of this theorem in more detail, one finds that it does not just depend on the spin of the quanta. In the case of any pair of particles which interact by exchanging particles with integral spin j (in our case $j=1$ or 2) the momentum change p (or force) must vanish like p^j as p goes to zero. This would be a disaster for the conventional theories, because the major effect observed for small p in electromagnetism is the Coulomb or electrostatic force between charges. For gravitation the only directly measured force is ordinary Newtonian gravity. The spin-2 “gravitons” which the theory predicts cannot be directly detected, and whether classical gravitational radiation has been detected or not is controversial. The way conventional theory gets around this disaster is to insist that the theory be “gauge invariant” as well as “Lorentz invariant”. The low momentum limit— if one believes the somewhat tricky mathematics — then produces the desired Coulombic and Newtonian forces out of this theorist's hat. But, unlike fields which have a direct connection with the observed motions of test particles, “potentials” whether “gauge” or other, have no directly observable consequences. One is permitted to view them as theoretical inventions, rather than as a transcription of empirical fact into mathematics. I make the technical argument in a paper called *ANTI-HYDROGEN: The cusp between Quantum Mechanics and General Relativity*, available as SLAC-PUB-5856 (September 1992).

The end conclusion is that *if* anti-protons “fall” up, one will have to abandon *both* the equivalence principle (i.e. gravitational mass is identical to inertial mass) *and* relativistic gauge invariance. Such an experimental result would kill two theories with one measurement, which is a good investment when one is looking for a crucial experiment. Fortunately experimentalists are not deterred by theoretical arguments, and are forging ahead as carefully as they can. We may have the answer in five years.

Returning to H.G.Wells' Cavourite, the existence of gravitational charge still does not lead to it in any obvious way. We would have to wait for further articulation of the theory before we could figure out how to construct a bound matrix of gravitational charges and anti-charges. Then we could build a small and convenient space capsule similar to that envisaged by Wells. Anti-gravity by itself does not lead directly to star-ships. Project Sherwood will, some day, lead to practical magnetic "bottles" for protons, which would also work for anti-protons, provides interaction with the surrounding material is sufficiently rare. Making these tanks large enough to make the whole structure gravitationally neutral would, presumably, require a huge ship. But star ships have to be huge for other reasons. Although the overall configuration could be gravito-neutral, the distribution could have a non-spherical ("dipole") shape. Then internal fly wheels would allow something like Well's maneuvering techniques to be used. Direct use of anti-hydrogen as fuel could be reserved for impulsive jet "trimming" rather than using proton-antiproton annihilation directly as a rocket drive.

I have strong hopes that we may see a start on such projects within my own lifetime. I now have a toast for all occasions which I urge the rest of you to adopt:

UP THE ANTI-PROTON