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Abstract

The expression for the gravitational red shift has been derived without the equivalence principle. This allowed us to give the gravitational mass opposite signs for particles and antiparticles. It is shown that when an antinucleus emits or absorbs a photon, the antigravity produces an anomalous frequency shift in magnitude or sign, or both, depending on the emitter-absorber configuration. Whenever the antinucleus is used as an absorber, the shift will have a positive sign (blue shift). If an antinucleus emitter and a nucleus absorber were placed next to each other in a terrestrial laboratory, a gravitational shift would be produced about 10^6 times as large as the one observed by Pound and Rebka with nuclei. Measurement of the frequency of Balmer series emitted by the antihydrogen atom (antiproton plus positron) in the gravitational field of the earth could reveal the existence of such an effect. An extension of these considerations to the antinucleon-nucleon system suggests that an apparent energy unbalance of 2 ev (1 part in 10^9) should be observed in antiproton annihilations, as a consequence of such an anomalous gravitational shift. Although our present theoretical concepts leave no room for such effects, particularly those in electromagnetic transitions, their existence would not be in conflict with the actual experimental data, and establishing their absence would provide direct and unambiguous arguments against antigravity.

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Introduction

Although originally calculated from the time dilatation in a gravitational potential which follows from the principle of equivalence, the gravitational red shift can be derived without this principle. This was shown by Dicke.[1] We shall show here a simple derivation based only on the mass-energy relation $m = E/c^2$ and the Newton Law, and discuss the probable consequences of such an approach to the question of the gravitational mass of antimatter. We shall first assume that our approach is completely justified, as if the equivalence principle were not known, and shall derive its probable effects. These should stay qualitatively correct even if our assumption were only partially justified. The determination of the degree of correctness of this approach or, in other words, the degree of exactness of the equivalence principle in conditions in which both matter and antimatter are involved, will be left to the experiment. The purpose of this paper is to find an experiment which will be able to do this with the antiparticles available at present.

The equivalence of gravitational and inertial mass has been verified[2] with an accuracy of $1:10^8$, but under conditions in which only one kind of matter is investigated. As pointed out,[3] the accuracy with which the equivalence principle is established is perhaps conditioned by the accuracy with which antimatter is excluded from the experiment. Even if the nearest galaxy is made of pure antimatter, its antigravitational effects, if such exist, would affect the equivalence by less than $1:10^{15}$. Present theoretical conceptions on the problem of gravitational interactions leave no room for deviations from the equivalence principle. But the apparent success of the theories such as general relativity ought not to be allowed to prevent those physicists who still believe in the empirical character of their science from inquiring into possible experiments whose results could be given simple interpretations in terms of the existence (or nonexistence) of the difference between the gravitational masses of particles and antiparticles. For, from the point of view of experimental physics, pointing out a direct experiment which can be unambiguously interpreted (no matter how hard or unfeasible the experiment may be at the time) could be of greater value than a number of ingenious deductions from experiments performed in circumstances of limited generality.

Red Shift

There always exists an ambiguity in the definition of units of energy (or other quantities) at different space-time points. Thus one may, in a process of emission and absorption of electromagnetic radiation in a gravitational field, regard either the photon energy or atom energy as varying with gravitational potential. Here we regard the photon energy as fixed. From this point of view, two atomic systems at different gravitational potentials have different total energies. The spacings of their energy levels, both atomic and nuclear, differ in proportion to their total energies.[4] Let us consider two levels of a nucleus. Far away from gravitational bodies their energies are E_1 and E_2 and the energy of the photon emitted in a $2 \rightarrow 1$ transition if $E_\gamma = E_2 - E_1 = h\nu$. Special relativity ascribes equivalent masses

E_1/c^2 and E_2/c^2 to these levels. When they are brought to the terrestrial laboratory the gravitational potential of the earth will change the energies of the levels to $(E_1/c^2)(c^2+\phi_z)$ and $(E_2/c^2)(c^2+\phi_z)$,

where $$\phi_z = GM/(R+z) \qquad (1)$$

is the gravitational potential. Exactly at the earth's surface $z=0$, $\phi_z=\phi_0$, and the energy of the photon will be

$$E_0 = \frac{E_\gamma}{c^2}(c^2+\phi_0). \qquad (2)$$

On the other hand, an identical nucleus placed at height $z=Z$ will emit a photon of energy

$$E_z = \frac{E_\gamma}{c^2}(c^2+\phi_z). \qquad (3)$$

Subtracting Eq. (2) from (3), we get a difference in the photon energy produced by the difference in gravitational potentials at two heights $z=0$ and $z=Z$:

$$-\Delta E = E_z - E_0 = \frac{E_\gamma}{c^2}(\phi_z - \phi_0) \approx \frac{E_\gamma GM}{c^2 R}\left(\frac{z}{R}\right) = \frac{E_\gamma gz}{c^2} = E_\gamma z \times 10^{-18}\,\text{erg}, \qquad (4)$$

or

$$\Delta\nu = \nu z \times 10^{-18}\ \text{sec}^{-1}. \qquad (4')$$

The discerning reader will recognize in Eq. (4) and particularly (4') the (differential) gravitational red shift predicted by general relativity[5] and observed by Pound and Rebka.[6] In this approach, the photons are regarded as not changing their energy; the red shift results only from the difference in the gravitational and potential energies of the emitting and absorbing systems.

Antigravity and Anomalous Frequency Shifts

Schiff[7] and Good[8] have put forth strong evidence against antigravity. However, their arguments are necessarily somewhat indirect. The first kind of evidence[7] involves positrons in the virtual pairs of the Coulomb field of the nucleus in the light of the result of the Eotwos experiment. The second kind[8] of evidence is based on a well-accepted description[9] of K_2^0 mesons as mixtures of K^0 and $\overline{K}^0$ which are particles and antiparticles in the sense that they have opposite strangeness- a concept whose importance in description of stable matter in the universe is not clear.

Although the antigravity postulate would violate the well-established principle of equivalence and the principle of covariance, it would do so only in circumstances in which both types of matter are significantly involved.[3] It is generally accepted that it would be desirable to have the question of the sign of the gravitational mass of antiparticles settled by a direct experiment which could be unambiguously interpreted. What kind of experiment would this have to be? The most direct one would be to observe whether a horizontal beam of antineutrons is bent down or up. But the antiparticles produced by accelerators move almost at the velocity of light; in one kilometer of horizontal travel gravity would deflect them, up or down, only about 10^{-12} cm.

Let us consider what changes in the gravitational frequency shift would be brought about by introducing the assumption of antigravity into the approach by which we derived Eq. (4). We did not invoke the equivalence principle in that derivation, and therefore we can assign a negative gravitational potential to the antiparticles. We will "perform" four similar thought experiments.

a. A radioactive nucleus, say Co^{57}, at the earth's surface, $z = 0$, undergoes a transition, emitting a photon of energy $\frac{E}{c^2}(c^2 + \phi_0) = h\nu = 14.4$ kev. The photon is transmitted vertically up through a light pipe Z cm long. At the upper end of the light pipe there is another nucleus of Co^{57}. It is being moved up and down with a velocity Δv so as to compensate for the energy shift of the photon and bring it into resonance with the frequency ν. This is essentially the experiment of Pound and Rebka; as we know, the resonance absorption occurs when the velocity is directed downward and when the kinetic energy of the motion corresponds to ΔE given by Eq. (4), which is the differential red shift.

b. In the next experiment we use anticobalt-57 nuclei both as emitter and as absorber. The former is placed at $z = 0$ and emits a 14.4-kev gamma ray to the latter, which is placed at the upper end of the light pipe, $z = Z$. The antigravity assumption is equivalent to changing the sign of the ϕ, $\phi \to -\phi$, and the energy shift $\Delta E = h\Delta\nu$ becomes

$$E_z - E_0 = -\frac{E_\gamma}{c^2}(\phi_z - \phi_0) = +\Delta E. \qquad (5)$$

The sign of this shift is opposite to the one in Experiment a. The frequency shift does not change its magnitude, but it changes sign and becomes a <u>blue shift</u>. A similar result was obtained by Morrison and Gold.[3]

c. Next, we keep the anticobalt emitter at $z = 0$, but replace the absorber with an ordinary cobalt nucleus at $z = Z$. Then,

$$E_z - E_0 = \frac{E_\gamma}{c^2}(\phi_z - \phi_0) = \frac{E_\gamma GM}{c^2 R}(2 - \frac{z}{R}) \approx \frac{2R}{z}(-\Delta E). \qquad (6)$$

We again get a red shift, but this one is approx $2R/z$ times the differential shift given by Eq. (4)--i.e., an <u>anomalous red shift.</u> With the earth radius $R = 6.4 \times 10^8$ cm, and taking[4] $z = 3 \times 10^{12}$, this factor becomes approx 10^6. The magnitude of the differential shifts given by Eqs. (4) and (5) is a sixth-order effect, and this is why we have neglected it in Eq. (6). The experimental significance of the fact that the z/R term in (6) was neglected is that, contrary to the conditions in experiments a and b, here the emitter and the absorber can be placed next to each other on the earth's surface.

The "anomalously large" gravitational shift is actually the normal gravitational shift that would be seen from a point far removed from the earth, except that we have neglected the potentials of the sun, V_s, and galaxy, V_G. However, introducing these would amplify rather than weaken the effect, because

$$V_s + V_G > V_{earth} \quad .$$

d. Finally, we reverse the roles of emitter and absorber so that now the cobalt nucleus is at $z = 0$ and the anticobalt at $z = Z$. Then,

$$E_z - E_0 = -\frac{E_\gamma}{c^2}(\phi_z + \phi_0) = \frac{E_\gamma GM}{c^2 R}\left(2 - \frac{z}{R}\right) \approx \frac{2R}{z}(-\Delta E), \tag{7}$$

which represents a blue shift about 10^6 times the differential one in Eq. (5), i.e., an anomalous blue shift.

The antigravity postulate leads to dependence of observable quantities upon absolute gravitational potential, a concept which has an obscure physical meaning. This problem has been discussed by Good in some detail and the reader is referred to the source.[8] We can only stress that antigravity cannot be ruled out on this ground alone.

It should be pointed out that in general relativity, in a static mass distribution and static coordinate system, the red shift is determined by g_{44}. This is a scalar to the extent that these special coordinate systems can be chosen in an invariant manner. However, this is a nonlocal definition of the scalar.[1]

It is also interesting to note that the equivalence principle does not exclude the repulsion between gravitational bodies. In general relativity, the gravitational field of a body depends not only on its mass but also on the way it is stressed. A thrust or pressure augments the ordinary Newtonian gravitational force, but a tension reduces it. A body in a sufficiently high state of tension could exert a negative gravitational force--i.e., a repulsion.

We conclude, on the basis of the antigravity assumption, that the presence of antimatter in the universe must produce gravitational frequency shifts that are anomalous both in magnitude and in direction (sign).

Establishing that these shifts are absent would represent additional arguments against antigravity, if we believe that there is antimatter outside our galaxy.

On the other hand, the magnitude of the anomaly must depend on the matter–antimatter configuration surrounding the emitter of light outside our galaxy, which is not known. One can argue that no conclusions can be drawn before we perform an experiment under conditions such that this configuration is known.

What are the chances for making our thought experiments, say (c) or (d), real? Although the production of antinuclei, such as antideuterons, is a possibility, the production of radioactive antinuclei is at accelerator energies available today is impossible. However, the production of a bound state of positron and antiproton--the antihydrogen atom--in the reaction

$$e^{+} + \overline{p} \rightarrow \overline{H} + h\nu \tag{8}$$

is the simplest process involving antiparticles and a photon. As we have shown elsewhere,[10] the experimental problems associated with materialization of reaction (8) can be solved by using a mixture of relativistic or almost relativistic beams of antiprotons and positrons traveling in the same direction on parallel paths, but with slightly different velocities. Doppler-shifted photons from the capture process will be emitted forward together with the neutral antihydrogen atoms, while the rest of the particles, e^+ and $\bar{p}$, will be deflected in opposite directions in passing through a magnetic field. The position of the Balmer lines H_β, H_γ, H_δ, etc. from the cascade transitions of the captured electron, superimposed on the continuous recombination spectrum, should be measured in comparison with the same lines from ordinary hydrogen produced in identical experimental conditions. H_β is the first line whose width is comparable to the magnitude of the shifts given by Eq. (6) whereas already the H_δ line has a width about 1/10 of this shift.

Gravitational Energy Shifts in Antinucleon Annihilations

We shall turn next to the ideas of Morrison and Gold.[3] They modify the law of universal gravitation to the minimum degree necessary to maintain the consistency with other major physical postulates, yet to a sufficient degree to guarantee the separation of matter and antimatter in the universe. In their picture, only nucleons and antinucleons mutually repel gravitationally. The nucleon mass is a "gravitational charge" that can be of either sign, whereas all other forms of energy, such as electromagnetic and binding energy, are mutually attracted in the Newtonian way to both nucleons and antinucleons.

Therefore, anomalous gravitational frequency shifts cannot be expected in electromagnetic transitions between antihydrogen and hydrogen, anticobalt and cobalt. Only if one compares gravitational parts of the total energy does one get the large shifts as obtained in Eq. (6), but this will not occur in any spectral lines, either atomic or nuclear. Only the gravitational effect of the reduced mass will manifest itself in the anomalous frequency shift; this is an effect of high order.

However, the antinucleon-nucleon annihilation energy should show an energy shift given by Eq. (6). This shift would be

$$-\Delta E = \frac{2GM}{c^2 R}\, 2\times 938 \text{ Mev} = 2.14 \text{ ev}, \tag{9}$$

which will require a measurement of the annihilation energy with an accuracy of 1 in 10^9. Such an accuracy is not inconceivable from the point of view of measuring techniques, but it requires the knowledge to the same degree of accuracy, of the kinetic energy of the antiproton before annihilation. An energy resolution of 10^{-3} to 10^{-4} could be achieved with much effort; unfortunately, anything that could approach the required resolution of 10^{-9} is impossible with the techniques available at present.

It should be pointed out that although most of the generally accepted theoretical concepts tend to make the antigravity postulate rather weak, neither its existence nor its discussed manifestations would be in conflict with the actual experimental data. However, my intention was not to put forth arguments for or against antigravity, but to point to the two types of experiments that should show the effects of antigravity <u>if</u> it exists. Absence of the anomalous red shift in the antihydrogen-hydrogen emission-absorption process, Eq. (6), and particularly the absence of the anomalous shift in the annihilation energy Eq. (9), would represent direct and unambiguous evidence against antigravity; such evidence certainly is not available at the present time.

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Footnotes

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9. This description is not to be taken too literally; if K^0 and $\overline{K}^0$ were particles of matter and antimatter, they should annihilate in a time much shorter than 10^{-8} sec, and the K_2^0 meson would not exist even without the antigravity.
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