

**On the Gravitational Mass of Antiparticles,
the Gravitational Energy Shift of Spectral Lines,
and the Principle of Equivalence.**

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In a letter to the editor by WINTERBERG ⁽¹⁾ it is pointed out that the experimental confirmation of the so called red-shift of light rays in a gravitational field, together with the law of conservation of energy, makes it impossible to attribute to antiparticles a different gravitational interaction with matter than to particles. For example, according to ref. ⁽¹⁾, it would be possible to prove that the interaction has to be not only of the same magnitude but also of the same sign.

The purpose of this note is to show that no conclusion regarding the gravitational interaction of antiparticles can be drawn from the gravitational frequency-shift experiments and the principle of conservation of energy.

We shall adopt for our discussion the version of Winterberg's deduction given in ref. ⁽²⁾.

A photon of energy $2mc^2 - \varepsilon$ « falls » from point *A* towards point *B* of lower gravitational potential gaining an en-

ergy ε . At *B*, in the presence of a very heavy nucleus it creates a particle-antiparticle pair at rest, of total energy $2mc^2$. If the antiparticles have the opposite interaction with the gravitational field than the particles, the pair is weightless and can be lifted to point *A* without performing work. Thus one arrives at the end of this process to a system of energy $2mc^2$ without external work having been performed, violating energy conservation.

It is, however, not clear what is meant by saying that the photon gains an energy ε by propagating from *A* to *B*. In fact, if we consider the closed system, photon plus gravitating body, the total energy *E* of the system must be constant while the photon propagates from *A* to *B*. Let us assume that this total constant energy *E* is just equal to the total energy of another system formed by the same gravitating body plus a particle-antiparticle pair at rest at *B*. Then, when the photon arrives at *B* it can (in the presence of a very heavy nucleus) create a pair at rest and thus the first system transforms into the second one of the same total energy *E*. Now, if this pair is assumed

⁽¹⁾ F. WINTERBERG: *Nuovo Cimento*, **19**, 186 (1961).

⁽²⁾ H. FRAUENFELDER: *The Mössbauer Effect* (New York, 1962), p. 61.

to have zero gravitational mass, the total energy of the system with the pair at B is the same as the total energy of the system with the pair at A . Thus, if we lift the pair from B to A without performing work on the system, we arrive at a state which has the same total energy E as the initial system in agreement with the principle of conservation of energy.

On the other hand, if the pair has positive gravitational mass a certain external work ϵ has to be performed to lift it from B to A and thus, the total energy of the system with the pair at A is $E + \epsilon$ and in this case the initial total energy E , while being enough to create a pair at B , is not enough to create it at A .

As has been pointed out before ⁽³⁾ a similar way of reasoning gives us a very simple interpretation of the gravitational shift of spectral lines. We shall put this argument in a somewhat different form.

According to the equivalence of energy and mass, it takes more external work to lift an excited atom (or nucleus) from B to A than to lift the same atom in its ground state. (Atomic or nuclear excitation energies are differences of binding energies and have therefore to be considered in the same way as the binding energies themselves; *i.e.*: as contributing to gravitational as well as to inertial mass.) Thus, in the system atom plus gravitating body the energy difference between excited and ground state is larger when the atom is at A than when it is at B . Therefore, if a transition from the excited state to the ground state at B produces a photon, the total constant energy of the system photon plus gravitating body is smaller than the energy necessary to excite the atom at A from the ground state to

the excited state in question, even if cases are considered for which the recoil energies of the emitting and absorbing atoms are negligible. It is easy to see that this difference accounts for the correct value of the red shift. (If the shift is of the same order or smaller than the natural width of the level in question, excitation is still possible, nevertheless the shift can be measured by recording the position of the absorption line *ref.* ⁽⁴⁾.) For the experiments where the recoil energy is made negligible in a certain fraction of the transitions by placing the emitting and absorbing nuclei in macroscopic crystals (Mössbauer effect) the same argument can be used by considering the work necessary to lift such a crystal when one of the nuclei is excited and when it is not.

From this point of view, the gravitational shift can be explained by using only the mass-energy equivalence of the special theory of relativity and the well-tested proportionality of inertial and gravitational mass of matter. The principle of equivalence does not enter in any more general form.

On the other hand, any speculation on the possibility of a different gravitational interaction between matter and antimatter, than between matter and matter has obviously to be based on the assumption of the nonvalidity of the principle of equivalence.

In fact, if a local gravitational field produces different accelerations of particles than of antiparticles, it would be possible to distinguish it from an accelerated frame of reference in which the accelerations would be the same.

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⁽³⁾ A. BOYLE and H. E. HALL: *Rep. Progr. Phys.*, **25**, 447 (1962).

⁽⁴⁾ R. V. POUND and G. A. REBKA: *Phys. Rev. Lett.*, **4**, 337 (1960).