Pound's Falling Light Experiment and Einstein's Elevator

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Abstract

The experiments with gamma radiation carried out by Pound et al. in the 1960s make use of the Mőssbauer effect. The counting rate of photons emitted from a height of h=22.5 m from a Fe^{57} source was measured versus the downward speed of the absorber. It was found that the minimum transmission occurred at a speed equal to gh/c, thereby indicating that the excess speed of light was (gh/c^2) c, i.e. the speed of light was found to be greater than c because of the gravitational effect on the photons. This is in very good agreement with the value predicted in 1907 by Einstein on the basis of his Equivalence Principle (EP) which claims that the effects of a gravitational field are indistinguishable from those of a uniform acceleration of the object. However, it is pointed out that the EP fails to account for the fact that both the speed of light and the associated frequency vary in the same proportion with position of the source in the gravitational field, thereby indicating that the associated wavelength is invariant; the Doppler effect, on the other hand, when applied for the case of upward motion of the laboratory toward the source, leads to the conclusion that the wavelength should decrease in the same proportion as the frequency increases. The fact that the effects of both gravity and the motion of circumnavigating atomic clocks need to be taken into account separately/additively to predict elapsed time delays measured relative to the corresponding clock that remained stationary at the originating airport is proof that the two effects are not equivalent. The Uniform Scaling method is described which accounts for differences in measured values obtained in two different rest frames for all types of physical properties, thereby satisfying the original purpose foreseen for the EP.

Keywords: Pound et al. experiments, Equivalence Principle, Gravitational effect on light speed, Uniform Scaling method

I. Introduction

In 1965 Pound and coworkers [1,2] carried out a seminal experiment to study the effects of gravity on radiation. There were several theoretical predictions at issue. One was to test whether light in the form of γ-radiation is affected by changes in gravitational potential. To this end, a γ-radiation source was mounted on the top of a building at a height of 22.5 m above the absorber on the ground. The goal was to measure the change ΔV in the speed of the light relative to the standard value of c. The value of ΔV was found to be in agreement with the prediction of Einstein's Equivalence Principle (EP) which he introduced in 1907. [3] It was found that the speed of light emitted by the γ-radiation source is greater than c by a factor of $S=1+ghc^{-2}$ (c is the speed of light in free space and g is the local value of the acceleration due to gravity). Further details of this experiment are discussed below, including an analysis of their relevance to the EP.

II. Results of the Pound et al. Experiment

It is useful to begin with a quote from ref. 1 which describes the essential nature of the EP. "Einstein proposed that no local experiment of any kind could distinguish between the effects of a gravitational field, on the one hand, and the effects of a uniform acceleration of the laboratory with respect to an inertial frame, on the other." This assertion is often expressed in the popular literature by the term *Einstein's Elevator*.

Pound and Snider assumed that radiation emitted from a light source located at a height h=22.5 m above the absorber would be equal to $c' = c + \Delta V$, where $\Delta V = gh/c$. The latter value is expected based on Einstein's prediction of a red shift of the frequency of radiation coming from the sun by a fraction of $S = 1 + ghc^{-2}$. The same value for S is obtained by combining Newton's inverse square law (ISL) with Einstein's mass-energy equivalence relation $E=mc^2$. [4] In that case, it is assumed that if the object with local energy $E=mc^2$ is located at a potential $\Phi = gh$, the corresponding energy measured below (i.e. with h>0) will be $Smc^2 = mc^2 + mgh$.

In the example cited, S-1 has a value of 2.45×10^{-15} .[5] This value is greater than zero, which therefore indicates that the value of the light speed at the source is greater than c, i.e. c'>c. In his biography of Einstein, Pais [6] quotes him as follows: "In this theory the principle of the constancy of light velocity does not apply in the same way as in …the usual relativity theory." The corresponding value of S-1 near the surface of the sun is 2.122×10^{-6}.

III. Critical Analysis of the Equivalence Principle

The Pound et al. experiment [1,2] demonstrates convincingly that the speed of light depends on gravitational potential. This is different from saying that the experiments constitute proof of Einstein's EP, however. For this purpose, one needs to consider if there are other explanations from standard theory for the effects predicted by the EP. More than this, one needs to make an exhaustive search for physical processes that are not consistent with the EP.

To start with, let us consider a hypothetical test of the measurement of the speed of light in a gravity-free region of space. If the laboratory were accelerated upward with speed $\Delta V = gh/c$, it is possible to compute the expected result for the change of light speed by using vector addition. The light would be approaching him from above with speed c relative to the light source, Since he is approaching the source in the opposite direction, it is expected on that basis that he will measure the speed of the light c' from his vantage point to be the sum of the two opposing speeds, namely as $c' = c + gh/c$, which is equal to $Sc = (1+gh/c^2)c$. The agreement with the EP prediction is perfect in this case.

Next consider the measurement of frequencies. In this case the Doppler effect can be used effectively. It states that for a standard frequency ν_0 measured in the rest frame of the light source, the value obtained by the observer will be $\nu = (1+v/c)\, \nu_0$. With $v=gh/c$, one therefore obtains the value of $\nu = (1+ gh/c^2)\, \nu_0 = S\, \nu_0$, again in agreement with the EP value.

There is also agreement for energies. We assume from the EP that an object at the higher potential of the light source has an energy of $E=SE_0 = Sm_0c^2$, where m_0 is the inertial mass of the object at rest. When the object is viewed by an observer who is accelerated upward with speed $v = gh/c$, his measured energy E is obtained from classical gravitation theory to be the sum of the potential energy m_0gh and the rest value m_0c^2, i.e. $E = m_0gh + m_0c^2 = Sm_0c^2$. Once again the value expected from classical theory is the same as that predicted by the EP.

Next consider how the value of the wavelength λ is changed by kinetic acceleration. The Doppler effect can also be applied for this prediction. In this case, the wavelength λ_0 of light from the source is decreased according to the Doppler formula: $\lambda = \lambda_0/ (1+v/c) = \lambda_0/ (1+gh/c^2)$. In this way the phase velocity $\lambda\nu$ is unchanged by kinetic acceleration, i.e. $\lambda\nu= \lambda_0\nu_0 =c$. It is therefore seen that the EP fails in this comparison because experiment finds that the ratio of energy (SE) to frequency (Sν) is independent of gravitational potential. Therefore, based on the expectation that the phase velocity of light in free space is equal to the actual value of the speed of light, one concludes that the associated wavelength does not vary with gravitational potential, i.e. $\lambda = S^0 \lambda_0= \lambda_0$. One can therefore tell the difference between the effects of a gravitational field and those, resulting from uniform acceleration of the laboratory with respect to an inertial frame in a local experiment by measuring the wavelength of light in each case. The EP successes in the other examples of the speed of light, frequency and energy are just coincidences in other words.

Measurements of wavelengths are not the only such differentiating example. Consider the separate effects on Planck's constant h. In the presence of a gravitational field, energy $E=SE_0$ and frequency $\nu=S\nu_0$, so according to Planck's law [7], $E/\nu = SE_0/S\nu_0,=h$, i.e. h is invariant to gravitational acceleration. On the other hand, the corresponding relationships for kinetic acceleration with speed v are: $E=\gamma(v)E_0$ and $\nu = \nu_0/\gamma (v)$, where $\gamma(v) = (1-v^2/c^2)^{-0.5}$. Consequently, $E/\nu = \gamma(v)^2 E_0/\nu_0 = \gamma(v)^2 h$ for kinetic acceleration, whereas its value is h in the case of gravitational acceleration.

It should also be noted that the frequency of the gamma rays in the Pound et al. experiment [1,2] *does not change* when the light falls between the source and the observer. Einstein made this point clear in his 1907 paper [1,8]. He remarked that the number of wave crests that reach an observer in unit time is unchanged by the latter's relative speed or position in a gravitational field. As Einstein argued, the reason the observer A on the earth's surface finds that the frequency of light is smaller for him (red shift) than for a counterpart B located at the surface of the sun is because A's unit of frequency is larger than B's, not because the frequency has changed during transit.

There is another related point regarding possible changes in the speed of light as it descends in a gravitational field. A photon/light has no gravitational mass and is therefore not accelerated in a gravitational field. Another way to express the same fact is to say that g=0 for a photon. This characteristic has been used in conjunction with Huygens' Principle to compute the angle of displacement of start images during solar eclipses [9-13]. Just as with frequencies, the reason the value of the light speed in the Pound et al. experiments [1,2] which is measured on the ground is greater by a factor of ($1+gh/c^2$) than that measured by an observer in the rest frame of the light source is because the unit of speed is less by this factor on the ground than that employed on the roof. The situation is different for massive objects, as one can calculate that the speed of an object in free fall once it reaches the ground is gh/c, i.e. g multiplied by the time of descent (h/c). One can therefore disagree with Pound et al.'s characterization of light as having an "apparent weight."

IV. Consequences of the Failure of the EP

The realization that the EP is not valid for all properties forces the conclusion that gravitational acceleration and kinetic acceleration are two distinctly different phenomena. Evidence for this is provided by the experiments carried out by Hafele and Keating in 1971 [14,15] with circumnavigating atomic clocks. They found that changes in the rates of the clocks had to be determined by taking separate account of gravitational and kinetic effects. In the former case, in each interval of the flight, the contribution ΔT_g to the rate of a given clock due to the effects of gravity was computed with the same formula as that used by Pound et al. in their experiments [1,2], namely as $(1 + gh/c^2)\,\Delta T$, where ΔT is the corresponding value measured on an identical clock located at the airport of origin.

An additional contribution ΔT_k in the same interval was based on the effects of kinetic acceleration. In this case it was assumed that the clock on the airplane was slowed down by a factor of $(1+ 0.5\, v^2/c^2) \approx \gamma\,(v)$ relative to a hypothetical clock located on the earth's polar axis (or alternatively relative to the rest frame of the earth's center of mass). The key point with regard to the EP is that the two effects (ΔT_g and ΔT_k) were simply added together to obtain the total elapsed time difference between any two atomic clocks. In other words, the effects of gravitational and kinetic acceleration were taken to be completely separate from one another.

These experimental relationships have been extended to cover the effects of gravitational acceleration and kinetic acceleration on a completely general basis (Uniform Scaling method [16,17]). The first step is to account for large gravitational potential differences. For this purpose one uses a general definition for S which involves the quantity $A_i = GM/c^2 r_i$ (G is Newton's Universal Constant, $G = 6{,}67 \times 10^{-11}\ Nm^2/kg^2$, M is the gravitational mass of the relevant active mass such as the sun, and r_i is the distance separating the object from the active mass). The value of S is then defined as the ratio A_o/A_p, where the index o refers to the observer and p refers to the object of the measurement. For small separations of h between the observer and object, the value of S reduces to $1+ gh/c^2$, the same value used in both the Pound et al. [1,2] and Hafele-Keating [14,15] studies.

The value of S is conveniently seen to be a conversion factor between the units employed in the two rest frames. In general, the purpose of the Uniform Scaling method [16,17] is to allow the observer to convert results obtained in the object's rest frame to the corresponding values expressed in the units employed by him in his rest frame. The conversion factor is equal to S for measurements of velocity, frequency and energy, but is equal to unity (S^0) for distances. The other gravitational conversion factors are always integral multiples of S. The corresponding value for the S exponent is -1 for both inertial mass and elapsed time. A summary of other S exponents is given in ref. 16 for a representative series of properties. The value of S for a given property can be deduced from knowledge of the composition of the property in terms of the three fundamental quantities: distance, time and inertial mass.

There is an analogous scaling system for kinetic acceleration. In this case, a parameter Q is needed which is similar in practice to S in the gravitational scaling of the object's properties. The definition of Q requires the knowledge of a specific rest frame, referred to as the Objective Rest Frame ORS, [18] relative to which the speeds v and v' of the observer and object, respectively, are computed. The value of Q is then defined as γ (v')/γ(v). The ORS is the ECM for the circumnavigating atomic clock experiment [14,15] and, more generally, it is the laboratory in which the accelerating force is applied. As for S, Q is the conversion factor for various properties, including the fundamental properties of inertial mass, distance and time. All kinetic conversion factors are integral multiples of Q, just as the gravitation scale factors are all integral multiples of S.

It should be noted that "role reversal" for the object rest frame and that of the observer leads to a corresponding quantity Q'= γ (v)/γ(v') = 1/Q. i.e. the reciprocal of the original factor. A similar situation exists for the gravitational scale factors; role reversal in this case leads to the reciprocal value S'= A_p/A_o, This reciprocal relation occurs in everyday conversions, for example, from m to cm and pounds to kg. More information about both the kinetic and gravitational scale factors may be found elsewhere. [16,17, 19].

V. Conclusion

Shortly after Einstein introduced his mass-energy equivalence relationship, he developed a novel approach to the theory of gravitation, the Equivalence Principle (EP). He concluded, in recognition of Newton's theory, that when an object is moved to a height h in a gravitational field with local acceleration g, its energy changes from its initial value of mc^2 to a final value of mc^2+mgh. He noted, however, that an observer moving with the object would still find that its energy is unchanged from its original value of mc^2. This fact could be reconciled by assuming that the unit of energy is greater by a factor of $S=1+gh/c^2$ for the latter observer than that employed by his counterpart at the original gravitational potential.

Einstein then conceived the idea, the EP, namely that the same effect results in the absence of a gravitational field when the observer is accelerated upward to a speed of v=gh/c toward the object. In accord with the Doppler effect, the observer finds that the energy of the object has increased by a factor of S=1 +v/c, similarly as is the case for the frequency of light emitted by a light source at the same potential. In both cases, the value of the property at the higher potential is increased by a factor of $S=1+gh/c^2$. He subsequently concluded that the speed of light must increase by the same factor, and indeed that all physical properties change in the same way with this amount of kinetic acceleration of the object as when it is accelerated downward in a gravitation field. The goal in the Pound et al experiments was to verify the prediction of the EP for the speed of light in free space.

It is easy to see, however, despite the common belief, that the EP is not completely general, contrary to Einstein's position. When the Doppler effect is applied to the wave length of the emitted radiation, the result is that it decreases by a factor of S^{-1}, i.e. the distance between wave crests is compressed by virtue of the upward motion of the observer with the same speed v=gh/c. Since both the speed of light and the corresponding frequency increase by the same factor S in the gravitational field, it therefore follows that the wavelength must be unchanged in order for the phase velocity of the light, i.e. the product of wavelength and frequency, to remain the same, i.e. the gravitational conversion factor is S^0 for wavelengths, not S^{-1}.

Experimental proof for the failure of the EP comes from the Hafele-Keating experiments with circumnavigating atomic clocks. The goal was to measure the elapsed times on various clocks under different conditions over an extended period of time. In order to obtain accurate results it was necessary to evaluate the effects of both the kinetic motion and the gravitational field on the clocks at each portion of the journeys. The two effects were added together to obtain the desired elapsed times. If kinetic acceleration and gravitational acceleration are simply two different sides of the same coin, it would be possible to consider either one of the effects while simply ignoring the other in order to determine the correct value. Instead it was necessary to add the two sets of results at each stage. The same additive procedure is employed for the atomic clocks of the Global Positioning system, so this procedure constitutes a violation of the EP on an everyday basis.

Pound et al. could have carried out their experiments without reference to the EP. Their experimental procedure involved using the Mőssbauer effect to emit gamma radiation from the roof of a building to the laboratory 22.5 below where an absorber was located. The key effect in the experiment was to monitor the transmission rate as a function of the downward speed of the absorber. On this basis it was found that a speed of 7.35×10^{-7} m/s led to minimum transmission. It was of course noteworthy that the corresponding value for the fractional variation of the light speed relative to c was equal to $S=(1+gh/c^2)$, which is exactly the value previously observed for the blue shift of the radiation frequency, as well as for the increase in photon energy. The results represent an astonishing confirmation of Einstein's prediction made over 50 years prior to the experiment, but only a misleading confirmation of the EP itself.

The Uniform Scaling method does not rely on the EP, but it does comport with Einstein's original conjecture that the units of physical properties are changed by the effects of gravitational acceleration. Two parameters S and Q are defined which are specific to any pair of rest frames. In each case all conversion factors between the observer and the corresponding rest frame of the object are integral multiples of the latter two parameters. The predicted results always preserve the laws of physics such as $E=mc^2$ and Planck's $E=h\nu$ relation in each rest frame on an instantaneous basis, so they are consistent with Galileo's Relativity Principle for inertial systems. Reversing the roles of the observer and object in each case is accomplished by using the reciprocal of the factors in the original direction, the same as for conversion factors employed for m and cm, lb and kg, and even for the monetary values of currencies in normal practice,

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