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A quantum view of photon gravity: The gravitational mass of photon and its implications on previous experimental tests of general relativity

Donald C. Chang

Hong Kong University of Science and Technology,
Clear Water Bay, Hong Kong
bochang@ust.hk

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General relativity (GR) is an important theory that requires very stringent tests. So far, its supporting evidence comes mainly from measurements of photon gravitational effects, including light bending near the Sun, gravitational lensing in some galaxies and gravitational redshift of light. These previous experiments were designed based on a hidden assumption, namely, the gravitational mass of a photon is zero; thus, light should not be bent in a gravitational field if there is no space-time curving. In this work, we showed that the gravitational mass of a photon is not zero. Instead, it is equal to its quantum mass, which can be determined from its momentum using the de Broglie relation. Based on this understanding, the gravitational effects of light can be explained more simply using quantum physics. Our findings suggest that, in order to fully evaluate the theory of GR, more stringent experimental tests are required. Some examples of future experiments for testing the principle of equivalence are proposed here.

Keywords: Photon; gravitational mass; quantum mass; gravitational effect of light; general relativity; gravitational redshift.

1. Introduction

One of the most important findings in modern astrophysics was that light does not travel in a straight line in a gravitational field. This finding is often cited as a convincing evidence for supporting the validity of the theory of general relativity

(GR), which proposed that space-time can be curved by the presence of mass.[1,2] In fact, many experiments aiming to test the GR were based on determining the gravitational effects of light, including (a) the observation of light bending near a star,[3,4] (b) lensing effect of a galaxy,[5–8] (c) gravitational redshift of electromagnetic wave[9–12] and (d) discovery of black holes.[13,14] All of these experiments involved measuring the behavior of light in a gravitational field. So far, the results of these experiments all claimed to be supportive of the GR.[3–16] However, there is still a question on whether such interpretation is unequivocal. Are there possible alternative interpretations? Can these observed gravitational effects of photon also be explained based on other physical principles? In this paper, we investigated if the reported gravitational effects of photon can be explained based on quantum physics. We found that, although the rest mass of a photon is zero, its gravitational mass is equal to its quantum mass which is not zero. Thus, it is not surprising that the photon should interact with a gravitational field regardless of the validity of GR. This new understanding can easily explain the results of most of the earlier experiments. The details of this alternative explanation are discussed in the followings.

2. Does a Quantum Particle with No Rest Mass Interact with Gravity?

Most of the previous experimental tests in support of GR were related to testing whether space-time is bent by gravity.[3,4,8,17] Their methods were to examine the pathway of light near a gravitational field. For example, a very well-known experiment claiming to support GR was the experiment done by Eddington during a solar eclipse in Africa.[3] He reported that star light passing the edge of the Sun was bent (see Fig. 1(a)). Similar experiments conducted later using radio-frequency wave also confirmed that electromagnetic wave is bent near a star.[4] Such experiments, however, did not directly test the principle of GR (i.e. the principle of equivalence (PE)). Instead, they tested whether light will pass a gravitational field in a straight

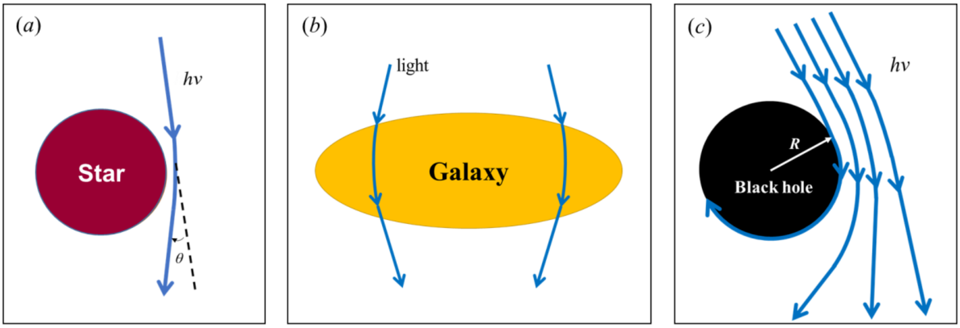

Fig. 1. (Color online) Bending of light by gravity. With the understanding that the gravitational mass of a photon is not zero, one can predict that the passage of light will be bent in a gravitational field. (a) Light deflection near a star; (b) lensing effect of a galaxy and (c) a strong gravitational field can prevent light to escape from the black hole.

line or not. If the star light is found to be curved, such finding would be consistent with the prediction of GR which proclaims that space-time can be curved by the presence of mass.

The design of these experiments, however, was based on a hidden assumption. That is, they assumed that, because photon has no rest mass, it should not interact with the gravitational field; thus, light should travel in a straight line near a star according to Newton's theory. But, is this assumption really correct? The key question here is: What is the gravitational mass of a particle? Is it the rest mass or the moving mass?

According to the Newtonian theory of mechanics, the gravitational mass of an object is identical to the inertial mass of the same object. This understanding was also supported by Einstein.[18–20] Since the inertial mass of a particle is its moving mass, there should be no doubt that the gravitational mass of a quantum particle should be its moving mass. In Newton's day, people thought the mass of an object is a constant. This understanding was changed at the beginning of the 20th century; it was discovered that the inertial mass (m) of a particle increases with speed,[21–25] such that

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}, \tag{1}$$

where m_0 is the rest mass of the particle and v is the velocity of the particle as measured against a stationary frame. For a massive particle, which is usually modeled as a point mass in the classical view, it is easy to calculate its inertial mass using the above equation. The gravitational mass of such a particle is the same as its inertial mass.

For a quantum particle such as the photon, the situation is slightly more complicated. This is because the photon has no rest mass (i.e. $m_0 = 0$). One may think that $m_0 = 0$ implies $m = 0$ according to Eq. (1). But this is not correct, because the speed of light is equal to c, so both the denominator and numerator of Eq. (1) are zero. The zero rest mass does not mean the moving mass (m) of a photon is zero. Then, we need to find another way to calculate the inertial mass of a photon.

Let us review first on what is the meaning of mass in physics. In Newtonian mechanics,

$$p = mv, \tag{2}$$

mass (m) is simply the proportional coefficient between the particle's momentum (p) and its velocity (v). In quantum mechanics, we know the momentum of a photon is given by the de Broglie relation,

$$p = \hbar k, \tag{3}$$

where k is the wave vector. We also know the speed of light is always c. Then, from Eqs. (2) and (3), we have

$$mc = \hbar k. \tag{4}$$

Thus, the inertial mass of a photon is

$$m = \frac{\hbar k}{c}. \tag{5}$$

So, it is clear that, for a quantum particle with no rest mass (such as photon), it can still have a nonzero inertial mass; we may call it the "effective mass" or the "quantum mass".

Then, the gravitational mass of a photon is simply its quantum mass as given in Eq. (5).

If one realized that the gravitational mass of a photon is not zero, one would expect that photon should naturally interact with a gravitational field; that means the trajectory of light should not be a straight line near a star (see Fig. 1(a)). Thus, the design of Eddington's experiments was on a faulty basis. Their experimental results could be interpreted either by the nonzero gravitational mass of a photon or by GR. It was ambiguous. (Of course, in the day of Eddington, people knew very little about quantum mechanics; he could not know that the quantum mass of a photon is not zero).

3. How to Explain the Lensing Effect of a Galaxy and the Formation of Black Hole?

3.1. *The lensing effect*

Another class of experiments claiming to support GR is the observation of the "lensing effect" of certain galaxies (see Fig. 2).[5–7,26] Many studies had used such lensing effect as evidence for supporting the prediction of GR that gravity is caused by space-time bending. Their conclusions, however, were also based on a faulty assumption similar to the Eddington experiment; namely, they assumed that the

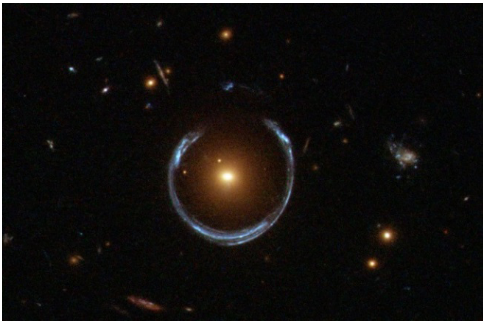

Fig. 2. (Color online) The lensing effect of a galaxy. The gravity of a luminous red galaxy (LRG) was found to distort the light from a more distant blue galaxy. The image of LRG 3-757 was first observed in 2007 from the Sloan Digital Sky Survey (SDSS); the image shown above is a follow-up observation taken with the Hubble Space Telescope.
Source: https://commons.wikimedia.org/wiki/File:A_Horseshoe_Einstein_Ring_from_Hubble.JPG.

photon has no gravitational mass. But as we pointed out in the above, their assumption was wrong. The lensing effect of a galaxy can be easily explained based on the fact that photon has a nonzero quantum mass and so it can be deflected in the gravitational field of a galaxy (see Fig. 1(b)).

Once one recognizes that the photon has a nonzero gravitational mass, one can immediately predict that a galaxy or a cluster of galaxies can produce a lensing effect to light rays emitted from distant stars. In most galaxies, a large amount of matters (including ordinary matters as well as dark matters) are concentrated at the center; their distribution is almost disk-like. This produces a gravitational field gradient. Since a photon has gravitational mass, its pathway will be bent by the galaxy's gravitational force when a light ray passes through the galaxy. As a result, the galaxy would appear to act as a lens (see Figs. 1(b) and 2).

Such lensing effect in fact is quite common in modern astrophysical studies. It was first observed in the double-imaged quasar in 1979.[5] Later, hundreds of gravitational lensing effects were reported by different groups.[6] For example, a strong lensing galaxy in the cluster IRC 0218 was identified using the Hubble Space Telescope. Due to its lensing effect, the image of the distant galaxy behind it was distorted to produce a counter image.[17]

3.2. *Black holes*

In the literature, another type of evidence for supporting GR is the discovery of black holes. The black hole is an object that generates a very strong gravitational force such that even light cannot escape from it. In the last 30 years, many black holes have been observed in different places of our Universe.[13,27] Some of the black holes at the center of galaxies can reach many million times of the mass of our Sun.[13]

The existence of black hole was reported to be one of the predictions given in GR.[11,27–29] Thus, the observation of black holes is considered to be a strong evidence for supporting GR. However, with the realization that the photon has a nonzero gravitational mass (m), one can also predict the existence of black hole based on the Newtonian gravitation theory.

The behavior of photon in a gravitation field is no different than an ordinary particle with mass. Suppose a massive object has a mass M_b, a particle (with moving mass m) flying nearby this object will experience a gravitational force. Suppose the velocity of this moving particle is u and the perpendicular distance between the particle and the massive object is R (see Fig. 1(c)). In order for the particle not to fall into that massive object, it needs to have a centrifugal force at least equal to that of the gravitational force, i.e.

$$\frac{mu^2}{R} = G\frac{mM_b}{R^2} \tag{6}$$

or

$$u = \sqrt{\frac{GM_b}{R}}. \tag{7}$$

This is the velocity required for the moving particle to counter act the attractive gravitational force of the massive object; it is called the "escape velocity". Now, if this escape velocity is equal to (or larger than) the speed of light (i.e. $u \geq c$), no particle (including photon) can escape the gravitational field of this massive object. Since the maximum velocity for any particle is c, all flying-by particles (including photons) will be captured by the massive object, which now becomes a "black hole".

From Eq. (7), one can calculate the size of a black hole; its radius is

$$R = \frac{GM_b}{c^2}. \tag{8}$$

Thus, the existence of black holes not only can be explained based on GR, it can also be explained based on the nonzero quantum mass of a photon (and the Newtonian theory).

4. How to Explain the Gravitational Redshift of Electromagnetic Wave?

4.1. *Gravitational redshift of electromagnetic wave according to GR*

In the literature, the most strong evidence cited for supporting the PE of GR was based on the measurements of the gravitational redshift of electromagnetic waves.[9–12] According to GR, time can be affected by gravity; and thus, it predicts that there should be a gravitational redshift of light.[30] Suppose a beam of laser light is transmitted from a ground station (point A) to a receiver in a satellite (point B) orbiting above the Earth (Fig. 3). The theory of GR predicts that the light will experience a gravitational redshift[31]

$$\nu' = \nu \exp\left(-\frac{\Delta\phi}{c^2}\right), \tag{9}$$

where ν' is the frequency of light at the satellite, ν is the initial light frequency at the ground station, $\Delta\phi$ is the difference of the gravitational potential between these two locations. Since the photon energy is much larger than the change of gravitational potential energy (i.e. $c^2 \gg \Delta\phi$), one can apply Taylor's expansion to the above equation and obtain

$$\nu' = \nu\left(1 - \frac{\Delta\phi}{c^2}\right). \tag{10}$$

Now, denoting the change of frequency as $\Delta\nu = \nu' - \nu$, the above relation gives

$$\frac{\Delta\nu}{\nu} = -\frac{\Delta\phi}{c^2}. \tag{11}$$

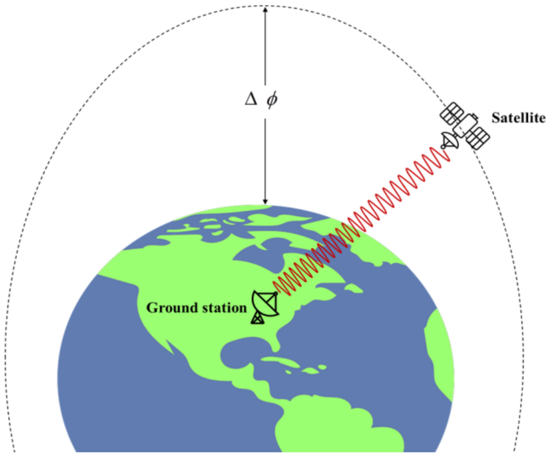

Fig. 3. (Color online) Gravitational redshift of photon. When a beam of electromagnetic wave is transmitted from a ground station at the Earth surface to a satellite, its frequency undergoes a redshift. $\Delta\phi$ is the gravitational potential difference between the receiver and the transmitter (in this illustration, the satellite is assumed to move in a circular orbit).

This is the well-known relation of gravitational redshift; it had been used in many experiments to test the validity of GR.[9–11] Such a relation is actually used in satellite communication today. For example, many receiver systems designed for satellite navigation are now incorporating the gravitational redshift effect.[32]

4.2. *Explanation of the gravitational redshift effect based on quantum physics*

So far, many experiments had been conducted on measuring the gravitational redshift effect of photon. Their data were all consistent with the prediction given in Eq. (11). Thus, it was claimed that the PE is well verified.[11,12,16] However, we found that the gravitational redshift effect is not exclusively based on GR. Instead, it can be easily explained by the fact that the gravitational mass of a photon is not zero.[33]

With the understanding that photon has a nonzero gravitational mass, one can easily explain why the frequency of light will change in a gravitational field. Since a photon has moving mass, it can interact with the gravitational field. This implies that,

$$\text{Total energy of a photon} = \text{Its quantum energy} + \text{Its gravitational potential energy.}$$

The quantum energy of a photon is given by Planck's relation; its gravitational potential energy can be calculated based on Newton's law. Thus, the total energy of a photon within a gravitational field is

$$E_{\text{total}} = h\nu + m\phi, \tag{12}$$

where m is the quantum mass of the photon as given in Eq. (5), ϕ is its gravitational potential at a particular position.

According to the principle of conservation of energy, the total energy of a photon moving freely in space should be conserved. When a photon moves from point A to point B and there is a gravitational potential difference between these two points, the photon will change its frequency from ν to ν' in order to satisfy the requirement of conservation of energy. That is,

$$\Delta E_{\text{total}} = h\Delta\nu + m\Delta\phi = 0, \tag{13}$$

where $\Delta\nu = \nu' - \nu$, and $\Delta\phi = \phi_B - \phi_A$ is the difference of the gravitational potential between point A and point B. By substituting Eq. (5) into Eq. (13), we get

$$\frac{\Delta\nu}{\nu} = -\frac{\Delta\phi}{c^2}. \tag{14}$$

Thus, one can predict that the photon must be redshifted when it moves from the Earth surface to a satellite above the Earth (see Fig. 3). Hence, with the understanding that a photon has a nonzero gravitational mass, one can easily explain the gravitational redshift of electromagnetic wave.

Very interestingly, our theoretical result obtained based on the quantum mass of a photon (i.e. Eq. (14)) is identical to the theoretical result based on GR (i.e. Eq. (11)). That means the gravitational effect can be explained either based on GR or quantum physics. Thus, the detection of gravitational redshift cannot be regarded as an unequivocal evidence for supporting GR.

5. Re-Examining the Physical Basis of GR: Is the Vacuum an Empty Space? Can One Test Whether the Principle of Equivalence is Correct or Not?

5.1. *Is the vacuum an empty space*?

Today, it is well known that the theory of GR is incompatible with quantum mechanics and the Standard Model of particle physics.[34–38] Particularly, the concepts of vacuum in these two theories are very different. GR, as a classical theory, treats the vacuum as an empty space. In fact, it must assume that there is no resting frame in our Universe. Otherwise, one can use this universal resting frame (i.e. the vacuum) to determine whether an object is in motion or not. This would allow one to differentiate between an object under acceleration and an object resting under gravity. Thus, if the vacuum is not an empty space, the PE cannot hold.

On the other hand, quantum mechanics treats the vacuum as a very complicated physical system. Its vacuum has very rich physical properties. It can only be regarded as the ground state of the quantum system.[25,34,38,39] In the Standard Model of particle physics today, it is thought that virtual particle pairs can be created or annihilated instantly in the vacuum. When energy is provided, the virtual particles can become real particles. If the vacuum is just an empty space, it is not possible to explain where these real particles come from.

Furthermore, the vacuum in modern cosmology is also not empty. For example, in the Big Bang model, our Universe is supposed to be originated from the quantum fluctuations of the vacuum.[39] These quantum fluctuations generated tremendous amounts of energy and created countless energetic particles in a fraction of a second. In a popular model of the Big Bang theory (the Inflation Model), such a process is very dramatic; the Universe can expand 10^{26} folds in $10^{-35}\cdot$ sec.[39]

Therefore, there is a huge conceptual difference between the empty vacuum model in GR and the quantum vacuum model in particle physics and cosmology today. In order to differentiate between these two models, it is tremendously important to test whether there is a universal resting frame in our Universe.

5.2. *Testing the principle of equivalence by measuring the mass variation due to speed changes*

In this work, we suggest that one possible way to test the PE is to measure the moving mass of an object over time. We know the inertial mass of a particle is its moving mass, which varies with the particle's velocity,

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}} = \gamma m_0, \tag{15}$$

where γ is called the "Lorentz factor". One can use the above relation to determine if a particle is at rest or under acceleration. The design of such an experiment is relatively simple. Supposed an object (with rest mass m_0) is placed on top of an "electronic balance" inside a rocket. The weight of this object is determined by the gravitational force and/or by the acceleration of the rocket. Let us consider two different motional states for the rocket (Fig. 4):

(A) The rocket is resting in a gravitational field (gravitational acceleration = g).

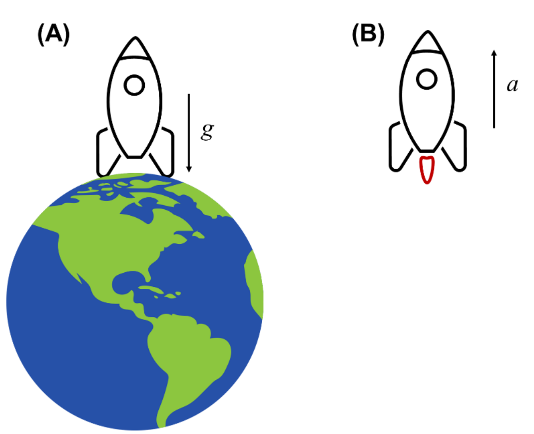

Fig. 4. (Color online) Two rockets in different situations: (A) the rocket is resting in a gravitational field; and (B) the rocket is under acceleration without gravity. According to GR, all physical experiments conducted within these two rockets should give identical results.

(B) The rocket is accelerating in the space (acceleration $= a$) where there is no gravitational force.

If $a = g$, the weight of the object will appear the same in both Case A and Case B. This is the basis for PE. However, if one can conduct an experiment inside the rocket to measure the weight of the object over a long period of time, it will be possible to determine whether the rocket is under acceleration or not. Under this situation, the PE would be violated.

To demonstrate this point, let us propose a very simple experiment. One can simply measure the weight of the object as a function of time and see if there is any change in its weight. At the beginning of the experiment, one cannot differentiate if the rocket is in motion or not. One could think the rocket is resting in a gravitational field (i.e. Case A) or under acceleration (with $a = g$) (i.e. Case B). But as time goes by, the speed of the rocket in Case B should increase with time, while the speed of the rocket in Case A will remain unchanged. That means the moving mass of the object in Case B should increase with time, while the moving mass of the object in Case A should remain constant (see Fig. 5). Based on such a measurement, one can determine whether the rocket is resting under gravity or accelerating without gravity.

5.3. *Designing an experimental apparatus to measure the variation of mass due to speed change*

One may worry that it is very difficult to find an electronic balance which is sensitive enough to detect the mass change, or, the balance may not work properly

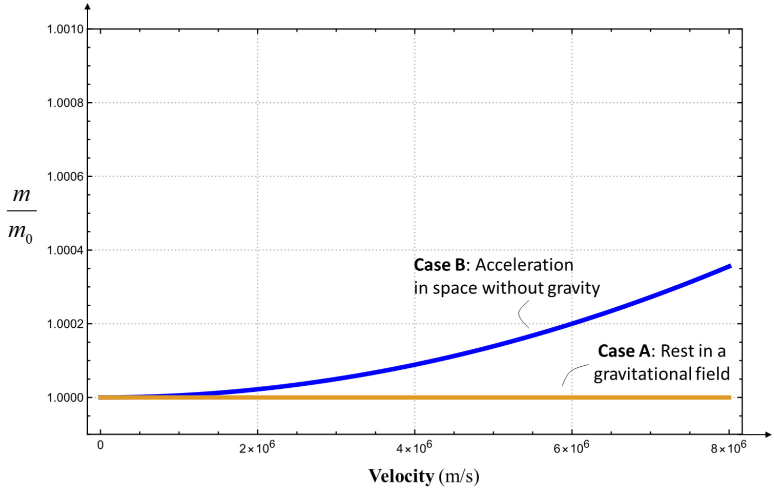

Fig. 5. (Color online) Differentiation between an accelerating rocket and a rocket sitting in a gravitational field. By measuring the mass variation with time, one can determine whether the rocket is under acceleration or resting in gravity.

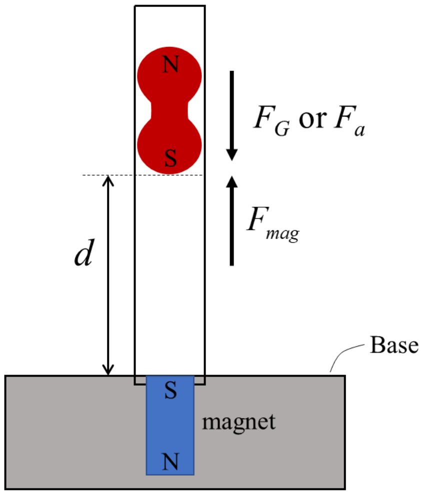

Fig. 6. (Color online) A simple apparatus for measuring the dynamic change of the "moving mass" of a mechanical object. Here, the repulsing magnetic force of the moving object is balanced either by its gravitational force or by its acceleration force.

under acceleration. There are many technical solutions to remove such worry. The experimental design for measuring the moving mass of an object does not need to be very complicated. For example, one can use a magnetic force (or electric force) to determine if the mass of an object inside the rocket has changed or not.

The design of such an experimental apparatus is shown in Fig. 6. A magnet is fixed at the base of the apparatus. The object to be measured is a floating magnet placed inside a (nonmagnetic) tube, which is put on top of the fixed magnet. The distance d between the floating magnet and the fixed magnet can be measured using a laser interferometer. The tube is parallel to the vertical axis of the rocket, so that when the rocket is accelerated, the acceleration force is parallel to the tube.

We know the magnetic force is

$$F_{\text{mag}} = \frac{\mu_0}{4\pi}\frac{M_1 M_2}{d^2}, \tag{16}$$

where μ_0 is the magnetic permeability of the vacuum, M_1 and M_2 are the magnetic charges of the floating magnet and the fixed magnet, respectively. In Case A, the gravitational force is $F_G = mg$, where $m = \gamma m_0$. The distance d is determined by the balance between the gravitational force and the magnetic force, i.e. $F_G = F_{\text{mag}}$, thus

$$mg = \frac{\mu_0}{4\pi}\frac{M_1 M_2}{d^2}, \tag{17}$$

$$d = \sqrt{\frac{\mu_0}{4\pi}\frac{M_1 M_2}{\gamma m_0 g}}. \tag{18}$$

Since the rocket is at rest in a gravitational field in Case A, there is no change in its speed. Thus, the Lorentz factor γ is a constant; d does not change with time. In fact, if the gravitational system can be taken as a stationary system, γ here would equal to 1.

In Case B, the situation is different. The force countering the magnetic force is an acceleration force,

$$F_a = ma = F_{\text{mag}}. \tag{19}$$

Since $a = g$, the distance d will be the same as that given in Eq. (18). However, because the rocket is under acceleration, its speed increases with time.

$$v = v_0 + at. \tag{20}$$

Thus, the value of the Lorentz factor γ would also increase with time,

$$\gamma = \frac{1}{\sqrt{1-(v_0+at)^2/c^2}}. \tag{21}$$

Thus,

$$d = \left(\frac{\mu_0}{4\pi} \frac{M_1 M_2 \sqrt{1-(v_0+at)^2/c^2}}{m_0 g} \right)^{1/2}. \tag{22}$$

As the speed of the rocket is far smaller than the speed of light, the above equation becomes

$$d \simeq \sqrt{\frac{\mu_0}{4\pi} \frac{M_1 M_2}{m_0 g}} \left(1 - \frac{(v_0+at)^2}{4c^2}\right) = d_0 \left(1 - \frac{(v_0+at)^2}{4c^2}\right), \tag{23}$$

where d_0 is d at rest. The above equation predicts that the measured value of d should decrease with time in a parabolic manner when the rocket is under acceleration (see Fig. 7).

The distance d can be measured using a laser interferometer, which can have a precision of 10^{-8} m or better. If the rocket is under acceleration, one should have no problem to detect its motion (say, when v reaches approximately 100 km/s, which is about 3 times the orbital speed of Earth around the Sun). Thus, from the results of the above experiment, one can clearly determine whether the rocket is in Case A (resting in gravity) or in Case B (accelerating without gravity). In another word, gravity and acceleration are not equivalent.

What we described above is an example of a relatively simple experimental setup. It is by no means the only experimental design for detecting whether the mass of an object inside the rocket can change due to acceleration. For example, one can modify the above-proposed experiment by using the Coulombic force between two charged objects to counter the gravitational force (or acceleration). A more sophisticated experiment can be done by measuring the mass-to-charge ratio of a charged particle using a mass spectrometer or a Penning trap.[40,41] For example, using the technique of Fourier-transform mass spectrometry,[42] one can determine

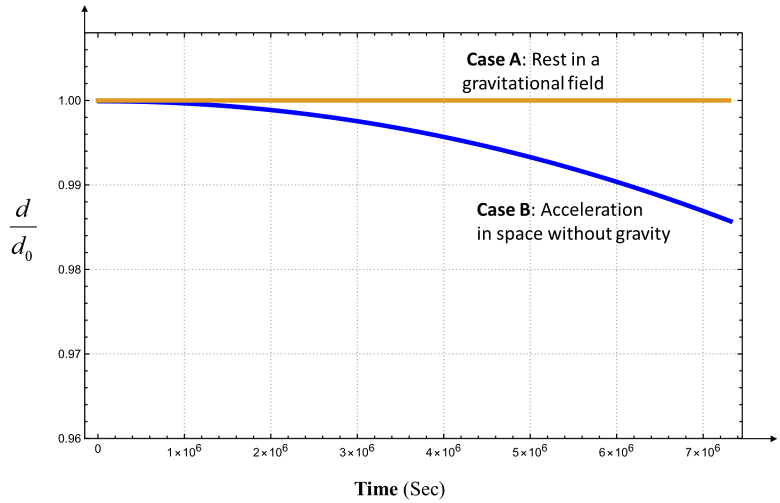

Fig. 7. (Color online) Expected results of mass measurements using an apparatus as described in Fig. 6. The dynamic change of the "moving mass" should be different between a system under acceleration and a system resting in a gravitational field. (Here the acceleration a is assumed equal to the gravitational coefficient g of the Earth).

the mass-to-charge ratio of a particle (such as an electron) to a precision of 10^{-8}. This is more than sufficient to determine whether the Lorentz factor γ would change with time due to rocket acceleration.

In summary, there are multiple ways to determine the moving mass (inertial mass) of an object when this object is in motion. Since the moving mass is a function of speed as given in Eq. (15), it is not difficult to differentiate whether an object is resting in gravity or accelerating without gravity. So, the proposal that gravity and acceleration are equivalent cannot be justified.

6. The Newtonian Theory of Gravity Needs to be Modified in View of Quantum Mechanics

"Mass" is a very important concept in physics. In classical mechanics, mass is regarded as an inherent mechanical property of an object which should be unchanged with time. But in modern physics, it was discovered that the mass of a particle can increase with speed, such that

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}. \tag{24}$$

Recently, we showed that the physical basis of this phenomenon is a quantum effect; it is because the particle is actually a quantized excitation wave of the vacuum.[25] Since Newton lived at a time far before the birth of quantum mechanics, he could not have knowledge about the speed-dependent relation of mass as shown in

Eq. (24). That is why in the traditional treatment of classical mechanics, the mass is often taken as the "rest mass".[43,44]

This classical view is not totally correct. As we pointed out in Sec. 2, since the gravitational mass of an object must equal to its inertial mass, the gravitational mass should be identified with the moving mass of the object. Based on this new understanding, we need to modify Newton's gravitation law to account for the speed-dependent change of the mass.

In another word, we should generalize Newton's gravitation law by identifying the masses of the two interacting objects (m and m') as their moving masses, i.e.

$$F = G\frac{mm'}{r^2} = G\frac{m_0 m_0'}{r^2}\ \{[1-(v/c)^2][1-(v'/c)^2]\}^{-1/2}, \tag{25}$$

where m_0 and m_0' are the rest mass of object #1 and object #2, v and v' are the speed of object #1 and #2 versus the vacuum. When the motion of the interacting objects is far slower than the speed of light, the higher order terms (v^4/c^4, v'^4/c^4, $v^2v'^2/c^4$, etc.) can be ignored, the generalize Newton's gravitation law then becomes

$$F = G\frac{m_0 m_0'}{r^2}\left[1 + \frac{1}{2}(v^2/c^2 + v'^2/c^2)\right]. \tag{26}$$

Thus, the gravitational force will not only depend on the rest masses of the interacting objects, it will also depend on the speeds of movement of the two interacting objects.

This point can be tested in experiment. One can carefully analyze the movement of planets around the Sun in the solar system. One may find that the movement could deviate slightly from the calculation based on the original Newton's law. Such deviations can be tested against the predictions as described in Eq. (26). Previously, it was observed that the orbit of Mercury does not agree exactly with the original Newtonian theory.[45] Our proposed generalization of Newton's gravitational law may offer a possible way to explain this disagreement.

The Newtonian theory and GR are classical theories; which assume that the gravity between two bodies is arisen from mutual attraction of their rest masses. From a quantum mechanical point of view, m is not a constant of the object. It was shown earlier that based on quantum physics, m is related to energy E,[25]

$$E = mc^2. \tag{27}$$

Since the mass of an object is no longer a constant, while we know the total energy of an object is conserved, it is more appropriate to regard gravity as a consequence of energy-attracting-energy. Newton's gravitation law can be re-written as

$$F = \frac{G}{c^4}\frac{EE'}{r^2}, \tag{28}$$

where E and E' are the total energy of the interacting bodies. Such energy not only includes the energy of the rest mass; it also includes the kinetic energy contributed from the momentum of the object. Since the total energy of a photon is never zero, from the above equation, one can easily see that the gravitational force between a photon and a massive object (such as a star) should not be zero.

7. Discussions

The general theory of relativity is an important theory in modern time. It has two major implications: First, the vacuum must be an empty space; there is no resting frame in our Universe. Thus, all motions are relative. Second, the four-dimensional (4D) space-time in our Universe is not fixed; it can be curved. The curving of space-time is due to the presence of local mass.

The question on whether the vacuum is an empty space is a very controversial subject. In the 19th century, many prominent physicists believed that the vacuum is filled with a medium called "aether".[46] This aether hypothesis was abandoned in the beginning of the 20th century, mainly due to its difficulty to explain the results of the Michelson–Morley experiment.[46,47] However, with the development of quantum mechanics, physicists later realize that the vacuum cannot be empty. According to the quantum field theory today, the vacuum has very rich physical properties; it is just the ground state of the quantum system.[25,34,38,39] Hence, the vacuum in quantum physics cannot be empty.[25,46,48,49]

Furthermore, there is also experimental evidence indicating that the vacuum is not empty. For example, the detection of Lamb shift in certain atomic orbitals indicated that electrons can polarize the vacuum in its vicinity.[50] Also, the zero-point energy of the vacuum can be detected based on the Casmir effect.[51,52] Today, it is a common understanding in quantum physics that the vacuum is not empty.

This modern understanding of the vacuum now raises a dilemma. If the vacuum is not empty, it can become a universal resting frame. One can clearly determine whether an object is in motion or not. If an object is under acceleration, the motion of the object can be detected by measuring the position of the object in comparison to the universal resting frame. One can clearly differentiate between acceleration and resting in gravity. That would violate the PE in GR.

As to the second implication of GR, many experiments had been conducted to test it. So far, most investigators claimed that their experimental results support the prediction of GR. Such experiments include the observation of light bending near a star, lensing effect of certain galaxies, observation of black holes and measurement of gravitational redshift of light.[3–17] Their results were all claimed to support the GR. However, there was a problem in these earlier studies. Namely, the investigators failed to consider alternative interpretations to their experimental results. In scientific studies, sometimes there could be more than one explanation for the experimental results. A careful investigator must consider the alternative interpretations and give reasons to rule them out. The earlier experiments claiming to support GR had not gone through such a process.[3–12,16]

In this paper, we examined whether those studies can be interpreted in an alternative way. Particularly, we examine if the observation on the gravitational effects of photon can be explained based on quantum physics. Indeed, we found most of the gravitational effects of photon can be explained based on the understanding that the gravitational mass of a photon is not zero. For a photon, the gravitational mass does not equal to its rest mass; instead, its gravitational mass is equal to its inertial mass as defined by its momentum. Using the quantum relation of de Broglie, the inertial mass of the photon can be easily derived (see Eq. (5)). Here, we call this mass of photon the "quantum mass".

Once we realize that the gravitational mass of a photon is not zero, it is expected that the photon should interact with the gravitational field. Thus, when the photon passes near a star, it should be attracted by the gravitational force of the star. This could immediately explain why light is bent near the Sun.[3,15] The same realization can explain the lensing effect of certain galaxies.[5,7] Since the mass in the galaxy is concentrated around its center in a disk shape, its strong gravitational field can bend the light passing through it like a lens. The same realization can also explain why black holes exist. Because photons have gravitational mass, if a massive astronomical object has sufficiently strong gravitational field, photons would not be able to escape from it. Such an object then behaves as a black hole.

Hence, most of the previous studies claiming to support GR could be explained based on the understanding that the photon has nonzero gravitational mass.

At present, the strongest evidence reported to confirm the PE was based on measurement of the gravitational redshift of light.[9–12] Their tests were based on an equation proposed by Einstein (i.e. Eq. (11)). However, we found that the gravitational redshift of the electromagnetic wave can also be explained based on an alternative basis. One can derive an equation for gravitational redshift identical to the Einstein equation based on the following assumptions[33]:

(1) The gravitational mass of a photon is its quantum mass as given in Eq. (5).
(2) When a photon travels freely in a gravitational field, it obeys the law of energy conservation.

Thus, an experiment measuring the gravitational redshift of the electromagnetic wave is not a direct test of GR; since the result can be explained also by the quantum theory.

Hence, there is still a lack of conclusive evidence that can unequivocally verify GR. The research of science is an endless effort of seeking truth. During this process, one will try to find the simplest hypothesis that can explain most of the experimental results (so-called the Occam's Razor). This is a fundamental spirit of science. In the future, if one wants to fully test the validity of GR, he must come up with more stringent experimental tests; that is, the experimental results can only be explained based on GR but not other physical principles.

8. Conclusion

The major finding in this paper is that the gravitational effects of light can be explained directly based on quantum physics. GR is a very important theory in modern physics. In the literature, many experiments had been reported in support of the GR. Most of these experiments involved measuring the behavior of photons in a gravitational field. They assumed that the gravitational mass of a photon is equal to its rest mass, which is zero. Thus, light should not be bent in a gravitational field if there is no space-time curving as suggested by GR. In this work, we showed that the gravitational mass of a photon is equal to its quantum mass, which can be determined from its momentum using the de Broglie relation. Based on this understanding, the gravitational mass of a photon is not zero. Therefore, most of the previous experiments claiming to test the validity of GR were based on a faulty assumption. With the realization that the gravitational mass of a photon is not zero, there is no surprise that light should be bent in a gravitational field. Furthermore, we showed that the nonzero gravitational mass of photon can also explain the gravitational redshift of light.

Our results suggest that, in order to critically evaluate the validity of GR, it is essential to conduct new experimental tests more stringent than measuring the photon gravitational effects. These future experiments could be designed to test two specific implications of the PE: (1) Is there a resting frame in our Universe? (2) Can one conduct a measurement to differentiate an object under acceleration from an object resting in a gravitational field? At present, it is already well known that the vacuum is not empty.[53] In fact, it is possible to design an experiment to directly test whether there is a resting frame in our Universe or not.[54] As to the second question, we suggested here a new experiment to test it by using the quantum phenomenon of speed-dependent variation of mass.

Note Added in Proof

In this paper, we followed the modern practice that the test of general relativity is based on whether light can pass through a gravitational field in a straight line or not. For example, in his famous book "*A Brief History of Time*", Stephen Hawking wrote: "*the fact that space is curved (according to general relativity) means that light no longer appears to travel in straight lines in space. So general relativity predicts that light should be bent by gravitational fields.*" Historically, this was not exactly correct. In Einstein's 1911 paper (*Annalen der Physik*, **35**, 1911), he predicted that if one combines the Principle of Equivalence and Newton's Law, light could be deflected near a gravitational source (such as the Sun). Later, when he developed the theory of general relativity in 1916, he found the predicted deflection angle was twice as large as what he predicted in the 1911 paper. So, in Einstein's mind, the predicted difference between Newton's law and General Relativity is not whether light will be deflected in a gravitational field; the difference is the degree of deflection. And this was what Eddington's famous experiment conducted during the 1919 eclipse expedition tried to determine. Their results were widely claimed to be supportive of Einstein's theory of general relativity. However, the quality of their data was really not conclusive. As pointed out by Stephen Hawking, "*It is ironic, therefore, that later examination of the photographs taken on that expedition showed the errors were as great as the effect they were trying to measure. Their measurement had been sheer luck, or a case of knowing the result they wanted to get, not an uncommon occurrence in science.*"

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