The Free Fall of Photon in Gravity

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Abstract

We calculate here the acceleration of point mass and photon by gravity. We discuss the motion of photon accelerated by gravity and we discover substantial statements leading to the physical meaning of photon.

1 Introduction

It is well known that Galileo performed experiment in Pisa - later the famous experiment - with the result that the every falling body is falling with a uniform acceleration, the resistance of the medium being through which it was falling remained negligible. He also derived the correct kinematic law for the distance traveled during a uniform acceleration starting from rest, namely, that it is proportional to the square of the elapsed time. Prior to Galileo, Nicole Oresme, in the 14-th century, had derived the times-squared law for uniformly accelerated body, and Domingo de Soto had suggested in the 16-th century that bodies falling through a homogeneous medium would be uniformly accelerated. Soto, however, did not recognize the strictly uniform acceleration is only in a vacuum, and that it would otherwise eventually reach a uniform terminal velocity. Galileo expressed the time-squared law using geometrical constructions and mathematically precise words (Frova et al., 2006).

We here consider the Galileo experiment with point mass and with photon. We discuss the motion of photon accelerated by the Newton forces and by gravity and we discover substantial differences leading to the physical meaning of photon.

2 The uniform acceleration of the non-relativistic massive particle

Let us consider the massive point with mass m accelerated by the constant acceleration a. The equation of motion is

$$\ddot{x} = a, \tag{1}$$

Let us introduce the the initial conditions

$$v(t = 0) = v_0. \tag{2}$$

Then we have from eq. (1)

$$\dot{x} = at + const, \tag{3}$$

where $const = 0$, if the initial conditions are $\dot{x}(0) = 0$.

The inititial condition (2) gives that the velocity of the massive body accelerated by acceleration a, leads to the law of the addition velocities. Namely, the final velocity $V(t)$ is given by the equation

$$V(t) = v_0 + at. \tag{4}$$

It means that the initial velocity is "absorbed" by the moving massive particle in order to conserve the addition law of velocities.

3 The uniform acceleration of the relativistic massive particle

In this case we apply the formula derived by Landau (1988). Namely:

$$\frac{d}{dt}\left(\frac{v}{\sqrt{1-\frac{v^2}{c^2}}}\right) = a \tag{5}$$

with the solution

$$\left(\frac{v}{\sqrt{1-\frac{v^2}{c^2}}}\right) = at + const. \tag{6}$$

If we postulate the initial condition by equation $v(t = 0) = v_0 = 0$,
then, $constant = 0$ and the explicit formal solution of eq. (6) is

$$v = \frac{at}{\sqrt{1+\frac{(at)^2}{c^2}}}. \tag{7}$$

After integration of eq. (7) with $x(0) = 0$, we get (Landau, 1988):

$$x = \frac{c^2}{a}\left(\sqrt{1+\frac{(at)^2}{c^2}} - 1\right). \tag{8}$$

For $at \ll c$, we get $v = at$ and $x = at^2/2$.

Now, let us consider the generalized situation with the adequate solution (Batygin, et al., 1978). A relativistic particle performs constant one-dimensional acceleration motion with acceleration a. The initial velocity is $v(t=0) = v_0 \neq 0$ and initial coordinate position is $x(t=0) = x_0 \neq 0$. It is possible to prove, that the solution of the problem is, with removing of some typographical errors, as follows (Batygin et al., 1978).

$$v = \frac{\left[at + \frac{v_0}{1-\frac{(v_0)^2}{c^2}}\right]}{\sqrt{1 + \frac{1}{c^2}\left[at + \frac{v_0}{1-\frac{(v_0)^2}{c^2}}\right]^2}} \tag{9}$$

$$x(t) = \frac{c^2}{a}\sqrt{1 + \frac{1}{c^2}\left[at + \frac{v_0}{1-\frac{(v_0)^2}{c^2}}\right]^2} - \frac{c^2}{a}\left(\frac{v_0^2}{1-\frac{v_0^2}{c^2}}\right) + x_0. \tag{10}$$

In the case with $v_0 \to c$, we have from the last formulas:

$$v(t) \to \infty; \quad x(t) \to \infty. \tag{11}$$

So, we see, that if we apply the textbook definition of photon having the inertial mass, then we get the nonphysical result. The resolution of this contradiction is, however, elementary: photon is a particle with no gravity mass. It is not excluded, that the last statement will lead to the revision of some texbooks and monographs on gravity physics and it will lead to the new development of theoretical and experimental physics.

In the non-relativistic limit we get from eqs. (9) and (10):

$$v(t) \approx v_0 + at; \quad x(t) \approx x_0 + v_0 t + \frac{1}{2}at^2. \tag{12}$$

4 The photon in gravity

What is photon? The photon is a type of elementary particle. It is the quantum of the electromagnetic radiation in the form of light and radio waves, and it is also carrier of the electromagnetic force. Photons are massless, and so they always move at the speed of light in vacuum, 299 792 458 m/s. Now, we know, that photon is the excited state of vacuum. So, photon is an analogue of phonon. Of course, the phonon velocity depends on the microscopical structure of the medium, where the phonon is created.

To be pedagigtcally clear, a phonon is a collective excitation in a periodic, elastic arrangement of atoms, or molecules in condensed matter, specifically in solids and some liquids. The physical nomenclature of phonon quasiparticle. Phonons can be thought as quantized sound waves, similar to photons as quantized light waves. The concept of phonons was introduced in 1932 by Soviet physicist Igor Tamm.

The photon belongs to the class of bosons. Photons are currently best represented by quantum field theory as a particles with spin 1. Their behavior is of waves-particle duality. Albert Einstein, explained how matter and electromagnetic radiation could be in thermal equilibrium with one another. Planck proposed that the energy stored within a material object should be regarded as composed of an integer number of discrete, equal-sized parts. To explain the photoelectric effect, Einstein introduced the idea that light itself is made of discrete units of energy. In 1926, Gilbert N. Lewis introduced the term photon for these energy units.

Now, let us follow the Feynman derivation of the frequency of photon in gravitational field (Feynman , 2011).

A photon of frequency ω_0 has the energy $E_0 = \hbar\omega_0$. Since the energy E_0 has the gravitational mass E_0/c^2 the photon has a mass (not rest mass) $\hbar\omega_0/c^2$, and is "attracted" by the earth. In falling the distance H it will gain an additional energy $(\hbar\omega_0/c^2)gH$, so it arrives with the energy

$$E = \hbar\omega_0\left(1 + \frac{gH}{2c^2}\right) = \hbar\omega. \tag{13}$$

So, its frequency after the fall is $E/\hbar$, or,

$$\omega = \omega_0\left(1 + \frac{gH}{2c^2}\right). \tag{14}$$

So, we see that in derived formulas the velocity of light was unchanged. The change of the energy of photon is not involved in the velocity of light bat in the frequency of light. We know, from the classical relativistic monographs (Fock, 1964), that in case of the deflection of light by gravity, the dispersion of light and the shift of frequency of light by gravity is not considered. To our knowledge, these crucial problems was still not discussed in the relativistic journals.

Our ideas about relativity, quantum physics, and energy conservation all fit together only if Einstein's predictions about clocks in a gravitational field are right. The frequency changes are normally very small. For instance, for an altitude difference of 20 meters at the earth's surface the frequency difference is only about two parts in 1015. However, just such a change has recently been found experimentally using the Mössbauer effect (Pound et al., 1960). Einstein was perfectly correct.

Schwinger used elementary considerations to reproduce the four observational tests of the Einsteinian modification of Newtonian theory, including the gravitational red shift (Schwinger, 2018). His argumentation is as follows. A slowly moving atom of mass m has the total energy

$$m - (GM/R)m = (1 - (GM/R))m. \tag{15}$$

in the neighborhood of the body with mass M. The energy released in an internal transformation is thus reduced by the factor

$$1 - (GM/R), \tag{16}$$

which is the gravitational red shift.

This is in harmony with the modern approach to the definition of a clock. Einstein could not have imagined how the clock would appear to a moving observer, nor, how a moving clock would behave when observed from a frame of reference at rest. (Brillouin, 1970).

At this time, we have a clock that is very different from the one Einstein had in mind. He visualized a clock as a sort of radar apparatus emitting short signals and measuring time intervals between such sharp signals.

The interest is now shifted from mathematics to physical facts. This is stressed also by the remark that frames of reference must be heavy, and that we must not talk of accelerating or decelerating them arbitrarily. This provides a good representation of what happens when velocity remains constant, but we do not know and should not guess what may happen to an accelerated clock. (Brillouin, 1970).

Let us remark that the interpretation of the redshift in a static gravitational field, was performed by Okun et al. (Okun et al., 1999; 2000).

The exact motion of light in gravity is described by the Einstein theory as the motion of light in curved space-time, where the curvature is caused by gravity. The gravity theory is based on the Einstein-Hilbert field equations (EHFE). They are the space-time geometry equations for the determining of the metric tensor of space-time for a given arrangement of stress energy in the space-time. The inertial trajectories of particles are geodesics in the resulting geometry calculated using the geodesic equation.

There is the simple derivation of the EHFE given by Fock (1964). The similar derivation was performed by Chandrasekhar (1972), Kenyon (1996), Landau et al. (1988), Rindler (2003) and others. Source theory derivation of Einstein equations was performed by Schwinger in the known form (1970).

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = -\frac{8\pi\kappa}{c^2}T_{\mu\nu}, \tag{17}$$

where the appeared constant in the last equation is introduce to get the classical limit of the equation. κ is the gravitational constant and its numerical value is in SI units $6.67430(15)10^{-11}m^3.kg^{-1}.s^{-2}$ (CODATA, 2018).

The approximate solution of the last equation is as follows

$$ds^2 = (c^2 - 2U)dt^2 - \left(1 + \frac{2U}{c^2}(dx^2 + dy^2 + dz^2)\right). \tag{18}$$

The space-time element (18) is able to explain the shift of the frequency of light in gravitational field and the deflection of light in the gravitational field of massive body with mass M.

Now the question arises, what is the equation of motion of photon in a gravitational field. The general solution is beyond of the possibility of mathematical physics and the specific case is of no easy solution. Namely, the force acting on the point moving is the homogeneous gravitational field was calculated in the 3-form as follows (Landau, et al., 1988):

$$\mathbf{f} = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}}\left\{\mathbf{grad}\ln\sqrt{h} + \sqrt{h}\left[\frac{\mathbf{v}}{c}\mathbf{rot}\ \mathbf{g}\right]\right\}, \tag{19}$$

with (Landau, et al., 1988).

$$h = 1 + \frac{2\varphi}{c^2}, \tag{20}$$

where φ s gravitational potential generating the acceleration $\mathbf{g}$.

If we perform the application of the last formula on the photon motion, the problem is beyond of the standard problems of gravity physics. So, we have decided for the classical solution in the framework of the equations of mathematical physics.

5 Discussion

We have seen how to calculate the motion of the non-relativistic and relativistic massive point by the Newton force and by the gravity force which is the analogue of the experiment where Galileo dropped objects from the leaning tower of Pisa. Galileo have used two bodies made of the same material, differing only in size. He had in fact stated that, if the effects of air friction could be ignored, the two bodies would reach the ground at the same time. So, he supported the conclusion that the every falling body is falling with a uniform acceleration, the resistance of the medium being negligible. Galileo experimentation represented the kernel of scientific investigation and Galileo was keen to point this out (Frova et al., 2006).

Now, the Galileo experiments are related to the the principle of equivalence. The principle of equivalence states that it is impossible to distinguish between the action on a particle of matter of a constant acceleration, or, of static support in a gravitational field (Lyle, 2008).

We have seen (Pardy, 2021) that the motion of the accelerated string by the non-gravity forces differs from the motion of the string caused by the gravity with the same acceleration which means that the principle of equivalence is broken in this case.

The contraversions between different opinions can be easily solved with regard to the physical definition of gravity and inertia. Namely: gravity is form of matter in the physical vacuum. And inertia is the result of the interaction of the massive body with the quantum vacuum being the physical medium.

Let us remark, that free fall of the positronium is of the same law as the free fall of an electron, or, positron apart. Also, free fall of the protonium is of the same law as the free fall of the proton, or, antiproton apart. It was experimentally verified. It means that the charge interaction with gravity is zero. Gravity interact only with mass and the result of such interaction is the free fall with emission of gravitons. In case of the binary system it was confirmed by NASA and the spectral formula of the emission of gravitons by the binary was calculated by author (Pardy, 1983; 1994a; 1994b; 2011; 2018; 2019). In case of the existence of the gravitational index of refraction, the gravitational Cherenkov radiation is possible (Pardy, 1994c; 1994d).

While Galileo dropped objects from the leaning tower of Pisa, now, we have possibility to drop charged objects from the very high tower Burj Khalifa, in order to confirm the law that charged objects accelerated by the gravitational field do not radiate the electromagnetic energy. It is not excluded that such experiment with the adequate title Galileo-Pardy-Burj Khalifa project will be realized sooner, or, later. The project is cheaper than LHC.

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