A New Approach on the Photoelectric Effect

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When photons hit a material surface they exert a pressure on it. It was shown that this pressure has a *negative* component (*opposite to the direction of propagation of the photons*) due to the existence of the negative linear *momentum* transported by the photons. Here we show that, in *the photoelectric effect*, the electrons are ejected by the action of this *negative* component of the *momentum* transported by the light photons. It is still shown that, also the *gravitational interaction* results from the action of this *negative* component of the *momentum* transported by specific photons.

Key words: Photoelectric effect, Photoelectrons, Radiation Pressure, Gravitational Interaction.

1. Introduction

Besides energy the photons transport linear *momentum*. Thus, when they hit a surface, they exert a pressure on it. Maxwell showed that, if the energy U of the photons is totally absorbed by the surface during a time t, then the total *momentum* q transferred to the surface is $q = U/v$, where v is the velocity of the photons [1]. Then, a pressure, p (defined as force F per unit area A), is exerted on the surface.

In a previous paper [2], we have shown that this pressure has a *negative* component (*opposite to the direction of propagation of the photons*) due to the existence of the negative linear *momentum* transported by the photons, shown in the new expression for *momentum* q transported by the photon, i.e.,

$$\vec{q} = \frac{U}{\vec{v}} = \frac{hf - \frac{1}{2}hf_0}{\vec{v}} = \left(1 - \frac{1}{2}\frac{f_0}{f}\right)\frac{hf}{c}\vec{n}_r \qquad (1)$$

where f is the frequency of the photon and f_0 is a limit-frequency, which should be of the order of *10Hz* or less; $n_r = c/v$ is the index of refraction of the mean.

Equation above shows that for $f > f_0/2$ the resultant *momentum* transported by the photon is *positive*, i.e., if this *momentum* is absorbed by a surface, pressure is exerted on the surface, in the same direction of propagation of the photon. These photons are well-known. However, Eq. (1) point to a new type of photons when $f = f_0/2$. In this case $q = 0$, i.e., *this type of photon does not exert pressure when it incides on a surface*. What means that it does not interact with the matter. Obviously, this corresponds to a special type of photon, which we will call of *neutral photon*. Finally, if $f < f_0/2$ the resultant *momentum* transported by the photon is *negative*. If this *momentum* is absorbed by a surface, pressure is exerted on the surface, in the *opposite direction of propagation of the photon*. This special type of photon has been denominated of *attractive photon*.

Here we show that, in *the photoelectric effect*, the electrons are ejected by the action of the *negative* component of the *momentum* transported by the light photons. It is still shown that, also the *gravitational interaction* results from the action of the *negative* component of the *momentum* transported by specific photons.

2. Theory

The *photoelectric effect* was first observed in 1887 by Heinrich Hertz [3,4] during experiments with a spark-gap generator — the earliest form of radio receiver. He discovered that electrodes illuminated with ultraviolet light create electric sparks more easily.

Attempts to explain the effect by Classical Electrodynamics failed. In 1905 Einstein proposed that the experimental data from the photoelectric effect were the result of the fact of light energy to be carried in discrete quantized packets.

When a photon strikes on an electron the *momentum* carried by the photon is transferred to the electron. According to Eq. (1), the *momentum* transferred to the electron is given by

$$\vec{q} = \left(1 - \frac{1}{2}\frac{f_0}{f}\right)\frac{hf}{c}\left(\frac{c}{v}\right) = \frac{hf}{\vec{v}} - \frac{hf_0}{2\vec{v}} = \vec{q}_r - \vec{q}_a \qquad (2)$$

where $\vec{q}_r = \vec{F}_r \Delta t_r$ and $\vec{q}_a = \vec{F}_a \Delta t_a$. Thus, the electron requires a time interval Δt_r for absorbing a *quantum* of energy hf and a time interval Δt_a for absorbing a *quantum* of energy hf_0.

Assuming that the time interval required by the photon for absorbing a *quantum* of energy hf is proportional to the *power* of the photon $\left(hf^2\right)$, i.e., $\Delta t_r \propto hf^2$ and $\Delta t_a \propto hf_0^2$. Then, we get

$$\frac{\Delta t_r}{\Delta t_a} = \frac{f^2}{f_0^2} \qquad (3)$$

Since the expressions of $\vec{F}_r$ and $\vec{F}_a$ are given, respectively, by $\vec{F}_r = \vec{q}_r / \Delta t_r = hf / \vec{v}\Delta t_r$ and $\vec{F}_a = \vec{q}_a / \Delta t_a = hf_0 / 2\vec{v}\Delta t_a$, then , we obtain

$$\frac{F_a}{F_r} = \frac{1}{2}\left(\frac{\Delta t_r}{\Delta t_a}\right)\frac{f_0}{f} \qquad (4)$$

Substitution of Eq. (3) into Eq. (4) gives

$$\frac{F_a}{F_r} = \frac{1}{2}\frac{f}{f_0} \qquad (5)$$

This equation shows that the force $\vec{F}_a$ is directly proportional to the frequency f of the photon, and thus explains why *low frequency light* does not produce photoelectrons. *If the light incident on the electron has low frequency*, then the force $\vec{F}_a$ may not be strong enough to eject the electron (whatever the intensity of the light beam).Thus, in order to produce *the photoelectric effect* the *light* incident must have high frequency (upper spectrum of light).

In the case of the photoelectric effect we have $f >> f_0$, then $F_a >> F_r$. Thus, the resultant acting on the electron is $\vec{F}_r - \vec{F}_a \cong -\vec{F}_a$. Then, the condition for an electron be ejected from a metallic surface is

$$\left|\vec{F}_r - \vec{F}_a\right| r_e \cong \left|-\vec{F}_a r_e\right| = \varphi \qquad (6)$$

where r_e is the orbital radius of the electron and φ is the *work function*, which gives the *minimum* energy required to remove a delocalized electron from the surface of the metal.

Substitution of the expression of $\vec{F}_a$ into Eq. (6) yields

$$\Delta t_a = \frac{r_e h f_0}{2v\varphi} \qquad (7)$$

Substitution of the expression of Δt_a, given by Eq. (3), into Eq. (7), gives

$$\Delta t_r = \frac{hf^2 r_e}{2v f_0 \varphi} \qquad (8)$$

For example, in the case of a light beam $\left(f = 4.39 \times 10^{14}\,Hz; v \cong c\right)$, incident on a lamina of *Sodium* metal ($r_e = 9.3 \times 10^{-11} m$ and $\varphi = 2.75\ eV = 4.4 \times 10^{-19} J$ [1] [5]), considering $f_0 \approx 10 Hz$ [2], then Eqs. (7) and (8) give

$$\Delta t_a \approx 10^{-33} s \qquad (9)$$

$$\Delta t_r \approx 10^{-6} s \qquad (10)$$

Thus, we can conclude that *the electron is ejected by the action of the force* $\vec{F}_a$ *much before* the total absorption of the *quantum* hf. Therefore, the cause of the ejection of the electron *is not* the absorption of the *quantum* hf (as Einstein thought [6]), but the action of the force $\vec{F}_a$ (See Fig.1). Similarly, when an electron is pumped from an orbit to another - by the action of a light photon, it is *ejected* from its initial orbit by the force $\vec{F}_a$.

[1] The work function of *very pure Na* is 2.75 eV. The work function of not purified sodium is less than 2.75 eV because of adsorbed sulfur and other substances derived from atmospheric gases. The most common values cited on the literature are 2.28 eV and 1.82 eV.

Then, in its trajectory, the electron is "captured" in the upper energetic level E_f. Therefore, the electron will be pumped from the initial orbit to a final orbit[2] if $hf - \frac{1}{2}hf_0 = E_i - E_f$, where E_i is the initial energy in the initial orbit, E_f is the total energy in the final orbit.

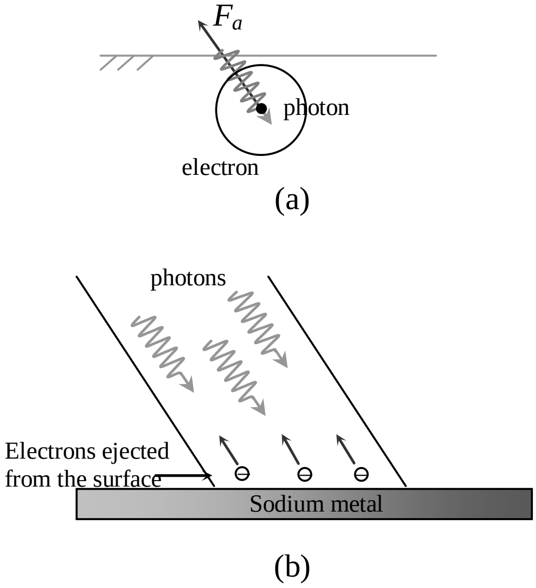

Fig. 1 - *The Photoelectric Effect*

Finally, we will derive the new expression for the *pressure* exerted by a radiation on a surface. From Eq. (2), we have $\vec{q} = \vec{q}_r - \vec{q}_a$. Thus, we can write that

$$\frac{\vec{q}}{\Delta t} = \frac{\vec{q}_r}{\Delta t} - \frac{\vec{q}_a}{\Delta t} \Rightarrow F = \frac{hf}{v\Delta t} - \frac{hf_0}{2v\Delta t} = \left(1 - \frac{f_0}{2f}\right)\frac{hf}{v\Delta t}$$

Therefore,

$$F_{total} = \left(1 - \frac{f_0}{2f}\right)\frac{Nhf}{v\Delta t} = \left(1 - \frac{f_0}{2f}\right)\frac{P}{v} \qquad (11)$$

where N is the total number of absorbed photons by the surface; P is the total power. Thus, the expression of the pressure, p, exerted by the radiation on a surface with area A is given by

$$p = \frac{F_{total}}{A} = \left(1 - \frac{f_0}{2f}\right)\frac{P}{Av} = \left(1 - \frac{f_0}{2f}\right)\frac{D}{v} \qquad (12)$$

where D is the power density of the radiation. Note that, only for $f >> f_0$ the equation above reduces to $p \cong D/v$ (the well-known expression for *radiation pressure*).

The law of inverse square of the distance, which is implicit in the Newton's law, shows that gravitation is propagated spherically. This reveals the principle of diffusion of the gravitational energy, i.e., it is transmitted by *waves* (or *photons*). The Quantum Field Theory shows that the gravitational interaction results from the interchange of a type of "virtual" *quantum*. Then, based on the above exposed, we can conclude that this *typical* "virtual" *quantum* is a *typical* "virtual" *photon*. Thus, we can say that the gravitational interaction, between two particles with gravitational masses m_{g1} and m_{g2}, respectively, results from the action of an amount of energy related to $E_{g1} = m_{g1}c^2$, ejected from the particle 1 under the form of N_1 "virtual" photons with a *typical* frequency f_g, and an amount of energy related to $E_{g2} = m_{g2}c^2$, ejected from the particle 2 under the form of N_2 "virtual" photons with frequency f_g.

Assuming that the amounts of energies ejected from the particles 1 and 2 are, respectively, $k_0 E_{g1}$ and $k_0 E_{g2}$, where k_0 is a constant, and considering that, according to Eq. (1), the energy of the photons is expressed by $hf - \frac{1}{2}hf_0$, then we can write that

$$k_0 E_{g1} = N_1\left(hf_g - \tfrac{1}{2} f_0\right) \qquad (13)$$

and

[2] *Independently* of the absorbing time Δt_r, which is of the order of $10^{-6}s$.

$$k_0 E_{g2} = N_2\left(hf_g - \tfrac{1}{2} f_0\right) \qquad (14)$$

Since

$$\left(\frac{A_1}{A_1}\right)k_0 E_{g1} = A_1 k_0\left(\frac{E_{g1}}{A_1}\right) = k_{s1}\left(\frac{E_{g1}}{A_1}\right)$$

and

$$\left(\frac{A_2}{A_2}\right)k_0 E_{g2} = A_2 k_0\left(\frac{E_{g2}}{A_2}\right) = k_{s2}\left(\frac{E_{g2}}{A_2}\right)$$

Then, Eqs. (13) and (14) can be rewritten as follows

$$k_{s1}\left(\frac{E_{g1}}{A_1}\right) = N_1\left(hf_g - \tfrac{1}{2} f_0\right) \qquad (15)$$

and

$$k_{s2}\left(\frac{E_{g2}}{A_2}\right) = N_2\left(hf_g - \tfrac{1}{2} f_0\right) \qquad (16)$$

where A_1 and A_2 are the incidence areas of the mentioned "virtual" photons, respectively on the particles 1 and 2 (See Fig.2); $k_{s1} = k_0 A_1$ and $k_{s2} = k_0 A_2$.

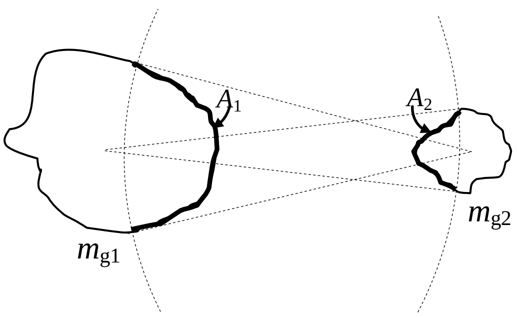

Fig.2 - A_1 and A_2 are the incidence areas of the "virtual" photons, respectively on the particles 1 and 2.

If the *forms* and the *gravitational masses* of the two particles *remain constants*, then E_{g1}/A_1 and E_{g2}/A_2 are *constants*, i.e.,

$$\frac{E_{g1}}{A_1} = k_1 \qquad (17)$$

and

$$\frac{E_{g2}}{A_2} = k_2 \qquad (18)$$

where k_1 and k_2 are constants.

From Eq. (17) and (18), we obtain

$$E_{g1}E_{g2} = k_1 k_2 A_1 A_2 \qquad (19)$$

By substitution of E_{g2} given by Eq. (14) into Eq. (19), gives

$$E_{g1} = \frac{k_0 k_1 k_2 A_1 A_2}{N_2\left(hf_g - \tfrac{1}{2} hf_0\right)} = \frac{K}{\left(hf_g - \tfrac{1}{2} hf_0\right)} \qquad (20)$$

Since N_1 and N_2 are pure numbers, then $k_0 k_1 k_2 A_1 A_2 / N_2$ is a *constant*, which here will be denoted by K.

On the other hand, we can write that

$$\frac{k_0 E_{g2}}{S_2} A_1 = n_1\left(hf_g - \tfrac{1}{2} hf_0\right) \qquad (21)$$

where n_1 is the number of photons incident on particle 1 and $S_2 = 4\pi r_2^2$, where r_2 is the distance from the center of the particle 2 to the center of the particle 1.

Substitution of $\left(hf_g - \tfrac{1}{2} hf_0\right)$ given by Eq. (20) into Eq. (21), gives

$$n_1 = \left(\frac{k_{s1}}{K}\right)\frac{E_{g1}E_{g2}}{S_2} = \left(\frac{1}{\alpha_1^2}\right)\frac{E_{g1}E_{g2}}{S_2} \qquad (22)$$

The constant K/k_{s1} has the dimension of $(force)^2$. Thus, k_{s1}/K was changed in Eq. (22) by the constant $1/\alpha_1^2$, where

$$\alpha_1^2 = \frac{K}{k_{s1}} = \frac{K}{k_0 A_1} = \frac{k_0 k_1 k_2 A_1 A_2}{N_2 k_0 A_1} = \frac{k_1 k_2 A_2}{N_2}$$

or

$$\alpha_1^2 = \frac{k_1 k_2 A_2}{N_2} = \left(\frac{E_{g2}}{A_2}\right)\frac{k_1 A_2}{N_2} = \frac{k_1 E_{g2}}{N_2} \qquad (23)$$

Substitution of N_2 gives by Eq. (16) into Eq. (23), yields

$$\alpha_1^2 = E_{g2}\left(\frac{hf_g - \frac{1}{2}hf_0}{k_0 E_{g2}}\right) = \frac{k_1\left(hf_g - \frac{1}{2}hf_0\right)}{k_0} \qquad (24)$$

Note in the equation above that the frequency f_g of the "virtual" photon (*quantum* of the gravitational interaction) is in fact *constant*, because α_1, k_0, f_0 and k_1 are constants. This confirms our initial hypotheses that the *quantum* of the gravitational interaction, is a photon with *a typical frequency*.

By analogy to Eq. (22), we can write that

$$n_2 = \left(\frac{k_{s2}}{K}\right)\frac{E_{g1}E_{g2}}{S_1} = \left(\frac{1}{\alpha_2^2}\right)\frac{E_{g1}E_{g2}}{S_1} \qquad (25)$$

Multiplying n_1 (Eq. 22) by n_2 (Eq. 25), we obtain

$$n_1 n_2 = \frac{1}{(\alpha_1\alpha_2)^2}\frac{E_{g1}^2 E_{g2}^2}{S_1 S_2} = \frac{c^8 m_{g1}^2 m_{g2}^2}{(\alpha_1\alpha_2)^2\left(4\pi r_1^2\right)\left(4\pi r_2^2\right)} \qquad (26)$$

where $S_1 = 4\pi r_1^2$; r_1 is the distance from the center of the particle 1 to the center of the particle 2. Since $r_1 = r_2 = r$, then Eq. (26) can be rewritten in the following form

$$n_1 n_2 = \frac{c^8 m_{g1}^2 m_{g2}^2}{(\alpha_1\alpha_2)^2\left(4\pi r^2\right)^2} \qquad (27)$$

According to Eq. (11), we can write that

$$F_1 = \left(1 - \frac{f_0}{2f_g}\right)\frac{n_1 hf_g}{c\Delta t_1} \qquad (28)$$

and

$$F_2 = \left(1 - \frac{f_0}{2f_g}\right)\frac{n_2 hf_g}{c\Delta t_2} \qquad (29)$$

whence we obtain

$$F_1 F_2 = \left(1 - \frac{f_0}{2f_g}\right)^2 \frac{n_1 n_2 \left(hf_g\right)^2}{c^2 \Delta t_1 \Delta t_2} \qquad (30)$$

Substitution of $n_1 n_2$ given by Eq. (26) into Eq. (30), yields

$$F_1 F_2 = \left(1 - \frac{f_0}{2f_g}\right)^2 \frac{\left(hf_g\right)^2}{\Delta t_1 \Delta t_2}\frac{c^6 m_{g1}^2 m_{g2}^2}{(\alpha_1\alpha_2)^2\left(4\pi r^2\right)^2} \qquad (31)$$

For $\Delta t_1 = \Delta t_2 = \Delta t_g$, we have $F_1 = F_2 = F$. Thus, Eq. (31) reduces to

$$F = \left(1 - \frac{f_0}{2f_g}\right)\frac{c^3\left(hf_g\right)}{4\pi\ \Delta t_g(\alpha_1\alpha_2)}\frac{m_{g1}m_{g2}}{r^2} \qquad (32)$$

In order to communicate ultra-small gravitational forces the energy $hf_g - \frac{1}{2}hf_0$ of the "virtual" photon (*quantum* of the gravitational interaction) must be also ultra-small. This means that, f_g must be less than $\frac{1}{2}f_0$ and *ultra close to* $\frac{1}{2}f_0$, i.e., $hf_g - \frac{1}{2}hf_0 = -\varepsilon \ \rightarrow 1 - f_0/2f_g = -\varepsilon/hf_g$, where ε is a *constant*. Thus, Eq. (32) can be rewritten as follows

$$F = -\left(\frac{\varepsilon\ c^3}{4\pi\ \Delta t_g \alpha_1 \alpha_2}\right)\frac{m_{g1}m_{g2}}{r^2} \qquad (33)$$

The term in parentheses must generate, obviously, the *universal gravitational constant*, $G = 6.67\times10^{-11} N.(m/kg)^2$, i.e.,

$$\left(\frac{\varepsilon\ c^3}{4\pi\ \Delta t_g \alpha_1 \alpha_2}\right) = G \qquad (34)$$

For $\Delta t_1 = \Delta t_2 = \Delta t_g$ and $n_1 = n_2 = 1$ (just *one* "virtual" photon incident on each particle) Eq. (30) gives $F_1 = F_2 = F_{\min}$, where $F_{\min}$ is the *minimal gravitational force* in the Universe, i.e.,

$$F_{\min} = \left(1 - \frac{f_0}{2f_g}\right)\frac{hf_g}{c\Delta t_g} = -\frac{\varepsilon}{c\Delta t_g} \qquad (35)$$

On the other hand, according to the Newton's law, we can write that

$$F_{\min} = -G\frac{m_{g\min}^2}{r_{\max}^2} = -\frac{\varepsilon}{c\Delta t_g} \qquad (36)$$

where $m_{g\min}$ is the gravitational mass of the material particle with *minimal mass* in the Universe, and $r_{\max}$ is the *maximal* distance (*diameter of the Universe*) between two particles of this type.

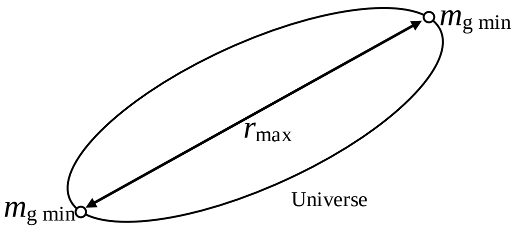

Fig. 3 –Two particles with the *minimal mass*, $m_{g\min}$, in the opposite positions (diametrically opposed) in the border of the Universe.

Based on Eq. (3), we can write that

$$\frac{\Delta t_a}{\Delta t_g} = \frac{f_0^2}{f_g^2} \qquad (37)$$

Since $\Delta t_a \approx 10^{-33} s$ (Eq. (9)), and as $f_g \lesssim f_0/2$, then Eq. (37) gives

$$\Delta t_g \approx 10^{-33} s \qquad (38)$$

Substitution of this value into Eq. (36), and considering that $m_{g\min} << m_{g(proton)}$ and $r_{\max} >> 2c/H_0$ (diameter of the *observable Universe*) where $H_0 = 1.75\times10^{-18} s^{-1}$ is the *Hubble constant*, then we can conclude that, ε must be ultra-small.

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