Radio Waves – Part III: The Photoelectric Effect

Explaining the Photoelectric Effect as an Effect of Electromagnetic Induction

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Abstract

In Part I of this series on Radio Waves I have tried to prove that *Maxwell's theory of electromagnetic waves*, claiming that a radio wave travelling in vacuum consists of oscillating electric and magnetic fields mutually inducing one another, is not supported by experiments, being based on assumptions and mathematical manipulations, and is therefore *untenable* because electric fields cannot exist in vacuum where there are no electric charges to produce them and because experiments have yet to prove that electric fields can be produced in vacuum by changing magnetic fields.

In Part II I have expressed the view that light and radio waves are waves in the aether, magnetic in nature, not containing electric waves, being described by the magnetic vector potential **A**, which corresponds to the velocity **v** of the flowing aether.

In this article I show that the views expressed above give a consistent explanation of the *photoelectric effect*. I will outline how do the experimental observations of the photoelectric effect summarized in the equation $hf = \frac{mv^2}{2} + W$, suggest that the photoelectric effect is a *Faraday effect of electromagnetic induction*. This is significant because, to the best of my knowledge, such an explanation of the photoelectric effect has not been advanced before, and because it proposes a mechanism by which the energy of a light wave is transferred to an electron without being necessary to introduce the hypothesis that light is composed of particles called photons.

Introduction

Ironically, the same scientist who proved the existence of radio waves, Heinrich Hertz, was the first to discover another phenomenon: the photoelectric effect. I call this an irony because, while Hertz's experiments with radio waves furnished support for the accepted idea that light is a wave, Albert Einstein used the photoelectric effect to argue precisely against this view claiming that, on the contrary, the photoelectric effect proves that light is a particle and that, as a consequence, a beam of light consists of a stream of such "particles of light" which he named "light quanta" or "photons".

You may be surprised to know that Einstein's hypothesis of the existence of "particles of light" was not accepted by anyone involved in experiments and observations of the photoelectric effect almost 100 years ago, since it was in gross contradiction with the view that light is a wave as proved in experiments of interference and diffraction.

Take the example of Robert Millikan, one of the scientists who did experiments that verified the laws of photoelectric effect and who finished his report as follows [*Proceedings of the National Academy of Sciences of the United States of America*, Vol. 2, No. 2 (Feb. 15, 1916), p. 78-83]:

> So far then as experiment has thus far gone, Einstein's equation seems to be an exact statement of the energies of emission of corpuscles under the influence of light waves.
>
> Nevertheless the physical theory which gave rise to it seems to me to be wholly untenable. Be this as it may, however, the photo-electric results herewith presented constitute the best evidence thus far found for the correctness of the fundamental assumption of quantum theory, namely, the discontinuous or explosive emission of energy by electronic oscillators. They furnish the most direct and most tangible evidence which we yet have for the actual physical reality of Planck's h.

"Nevertheless the physical theory which gave rise to it [Einstein's equation] seems to me to be wholly untenable."

Robert Millikan was not singular. O. W. Richardson had studied the emission of electrons by hot incandescent bodies (called thermionic, or thermoelectronic emission) and saw the photoelectric effect as a natural consequence of this phenomenon. He even developed a theory that accounted for the formula of the photoelectric effect in which he did not use the concept of light made up of photons. His article in *Science*, New Series, Vol. 36, No.

915 (Jul. 12, 1912), p. 77-58, concludes as follows:

> There is one other point. Equations (1)–(6) have been derived without making use of the hypothesis that free radiant energy exists in the form of "Licht-quanten," unless this hypothesis implicitly underlies the assumptions: (*A*) that Planck's radiation formula is true, (*B*) that, *ceteris paribus,* the number of electrons emitted is proportional to the intensity of monochromatic radiation. Planck[2] has recently shown that the unitary view of the structure of light is not necessary to account for (*A*) and it has not yet been shown to be necessary to account for (*B*). It appears therefore that the confirmation of equations (3), (5) and (6) by experiment does not necessarily involve the acceptance of the unitary theory of light.

"It appears therefore that the confirmation of equations [the laws of photoelectric effect] by experiment does not necessarily involve the acceptance of the unitary theory of light [existence of photons, or light-quanta]."

Another experimenter on the photoelectric effect was H. Stanley Allen. In his book, *Photo-electricity, the Liberation of Electrons by Light*, Longmans, Green and Co., London (1913), he discussed the various theories advanced for the explanation of the photoelectric effect. At page 146, he writes that "these theories [of particles of light, or quantum theory] are not accepted at the present time without a considerable reserve […].":

> Sir J. J. Thomson has put forward a theory as to the nature of light which helps to meet these difficulties. It is similar in character to the " quantum theory " developed by Planck and Einstein, which supposes that the energy in radiation is concentrated in discrete units. Although these theories are in accord with many of the facts of photo-electricity, they are not accepted at the present time without considerable reserve, mainly because they cannot be reconciled with the fundamental electro-dynamic equations of Maxwell and Hertz.

The theoretical solution offered by Albert Einstein was not satisfactory then and it remains unsatisfactory today because light (and indeed *any* natural phenomenon) cannot have *two* natures: light is either a wave or a particle and it cannot be *both* at the same time. The reason why physics still accommodates this inconsistent view of light is because no viable explanation of the photoelectric effect based on the wave theory of light was advanced since then.

I think that some of the reasons why one hundred years ago the photoelectric effect was hard to understand and explain in terms of the wave theory of light are that, in those times:

- there was a total confusion regarding the processes that take place in the source of light (be it a hot incandescent body, a flame, or a discharge or an arc lamp), as can be seen in the repeated revision of the law of radiation of incandescent bodies (the so-called "black-body radiation"): Rayleigh-Jeans, Wien, Planck,…;
- scientists did not realize that the measurement of changes in the intensity of light through its heating effect *does not necessarily imply* changes in the amplitude of the light wave;
- scientists did not realize that the transfer of energy in the heating effect (through which they measured the intensity of light) and the transfer of energy in the photoelectric effect occur by *two different mechanisms of energy transfer*;
- there was a total confusion regarding the true nature of light; thus, light was supposed to be: (i) a longitudinal wave of compression in aether (like sound in air); (ii) a transverse wave of aether (like water waves); (iii) a transverse electric wave (because Hertz called them so); (iv) a transverse electromagnetic wave (Maxwell's theory).

There were other adjacent shortcomings such as the incorrect interpretation of Faraday's experimental observations of the effect of electromagnetic induction, which was discussed in Part I of this series and will be taken up again in this work.

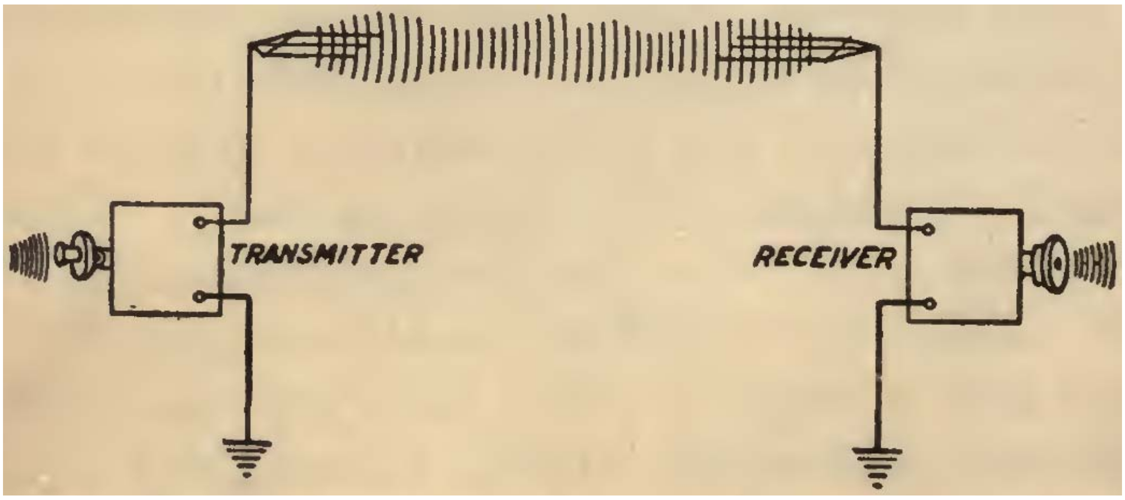
In these conditions, the further discovery that light expels electrons from a metal (the photoelectric effect) came to add difficulty to the riddle as it demanded a **mechanism** by which energy from the light wave was transferred to the expelled electron. And when you do not have a correct conception of what light is and how it is produced, how can you explain the effects it produces in its turn?

That light and radio waves are magnetic in nature consisting of compression waves in the aether I have discussed in the previous two parts of this series of Radio Waves. In an effort to show that this picture is consistent with other observed phenomena, the present work discusses the case of the photoelectric effect and shows that, just as the reception of radio waves by an antenna takes place through the effect of electromagnetic induction in the receiving antenna, the **mechanism** by which the energy of a light wave is transferred to an electron expelling it from a metal -the **photoelectric effect**- occurs through the same well-known **effect of electro-magnetic induction** discovered by Michael Faraday.

We will begin by discussing the perfect similarity between the two situations:
1. emitting antenna – radio waves – receiving antenna
and
2. light source – light waves – photoelectric tube

A. The similarity between the emission - reception of radio waves and the emission of light - photoelectric effect

In radio emission and reception the current oscillating in an antenna (called transmitting antenna) produces radio waves which, upon impinging on another similar antenna (called receiving antenna), produce electric currents in it.
The situation is shown schematically in the figure below, taken from Lewis F. Kendall, Robert Philip Koehler, *Radio Simplified*, The John C. Winston Company, (1923), p.12:



We have shown in Part II that the radio waves produced by the electric currents oscillating in the transmitting antenna are waves in the aether, magnetic in nature. The electric currents that these magnetic waves produce in the receiving antenna are due to the phenomenon of electromagnetic induction.

Now let us look at the situation in the photoelectric effect.

The figure below shows how the experimental setup for the study of the photoelectric effect is presented in textbooks; this particular one is taken from Arthur Beiser, *Concepts of Modern Physics*, 2nd Ed., McGraw-Hill Kogakusha, Ltd. (1973), p. 44, and it does not seem to indicate any similarity with the above situation of radio waves transmission and reception:

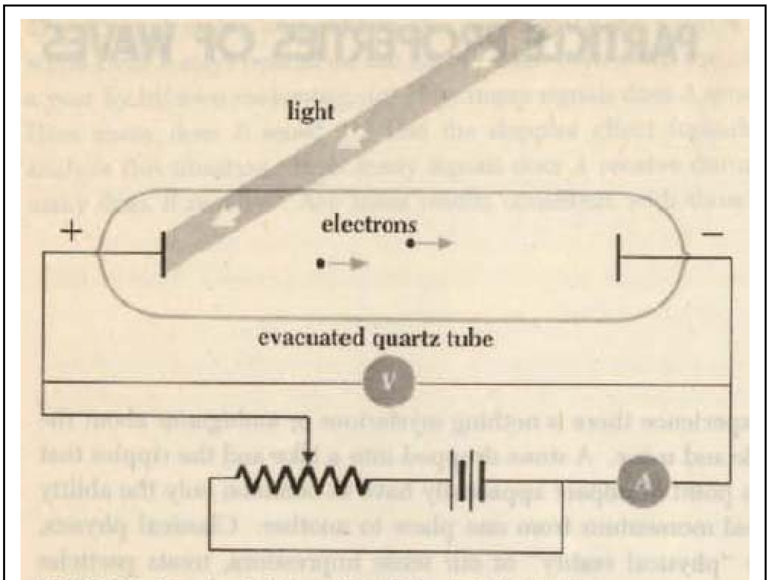
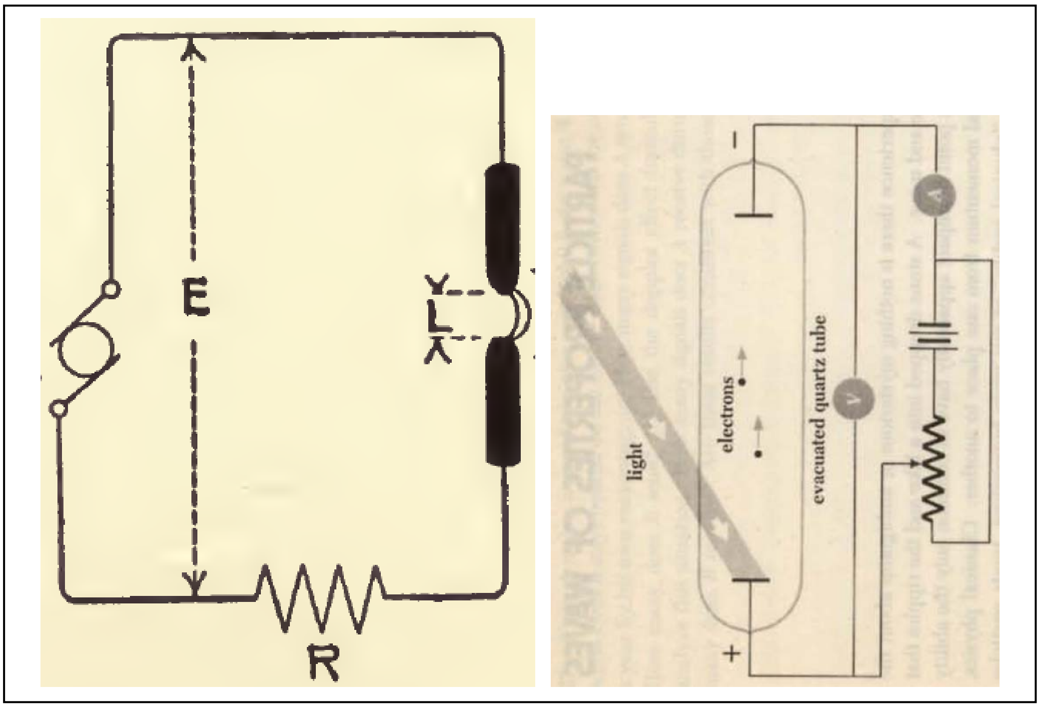


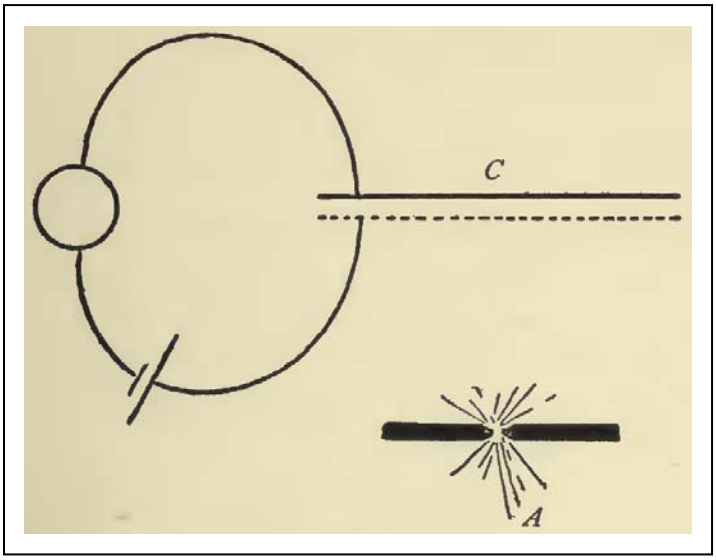
FIGURE 2-1 Experimental observation of the photoelectric effect.

The seeming lack of similarity with radio emission and reception is due to the fact that the source of light is not shown. Once we add to the picture the electric arc lamp that acts as a source of light, the similarity becomes apparent; in the picture below the arc lamp corresponds to the antenna emitting radio waves, while the photoelectric tube (an evacuated quartz tube in which electrons are pulled out from the illuminated electrode, travel through the vacuum of the tube to the other electrode and produce an electric current in the external circuit) corresponds to the receiving antenna; obviously, the light corresponds to the radio waves propagating through the aether.



[(left picture): Ewald Rasch, *Electric Arc Phenomena*, D. Van Nostrand Co., New York (1913), p.71; (right picture): Arthur Beiser, *Concepts of Modern Physics*, 2nd Ed., McGraw-Hill Kogakusha, Ltd. (1973), p. 44.]

That this is the complete setup in which the photoelectric effect is studied can be seen also in the following picture taken from J.J. Thomson's well-known *The Discharge of Electricity Through Gases*, Archibald Constable & Co., Westminster (1898), p. 67; observe the source of light A and the special capacitor C to study the photocurrent and connected with a battery and a galvanometer:



You may ask: but why is the source of light so important? Is it not simpler to study the photoelectric effect by just considering that light from *any* source simply falls on the metal surface of the photoelectric tube and produces an electric current?

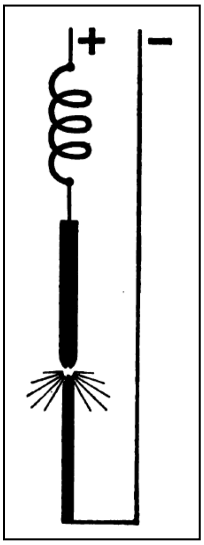
No, it is not simpler, the source of light is as important as the photoelectric tube because <u>the laws of the photoelectric effect depend on the frequency f as well as on the intensity I of the light</u>, and we have to know how light is produced in order to understand what happens when light intensity I is said to increase or decrease or when its frequency f increases or decreases.

This we will discuss in the next section.

B. Light sources: how is light produced and what happens in the source when the light it emits has greater intensity or frequency

In photoelectric experiments the sources of light used were: (i) Nernst lamps, (ii) arc lamps and (iii) gas-discharge lamps. In all of them a solid or gaseous substance, which is an assembly of *a great number of atoms*, was heated to very high temperatures; thus the atoms were collectively brought in a state of vibration and caused to emit light.
We see therefore that it is of importance to know how light is emitted by hot bodies.

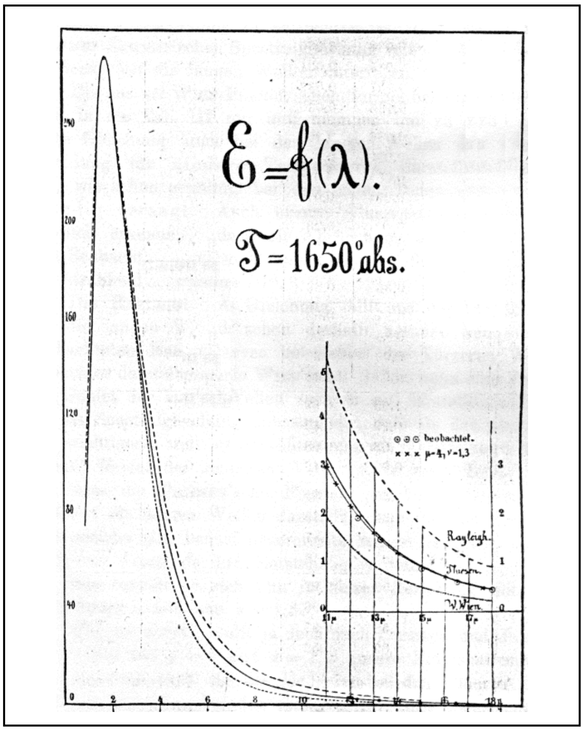
Look below at a picture of an arc-lamp in which a discharge passed in air between two carbon electrodes [J. Zeidler and J. Lustgarten, *Electric Arc Lamps, Their Principles, Construction and Working*, D. Van Nostrand Company, New York (1908), p.19, 2-4]:



The temperature of the carbon electrodes was estimated at 3500-3900°C (for the positive) and 3000°C (for the negative). Light was emitted by the volatilized carbon burning in air.

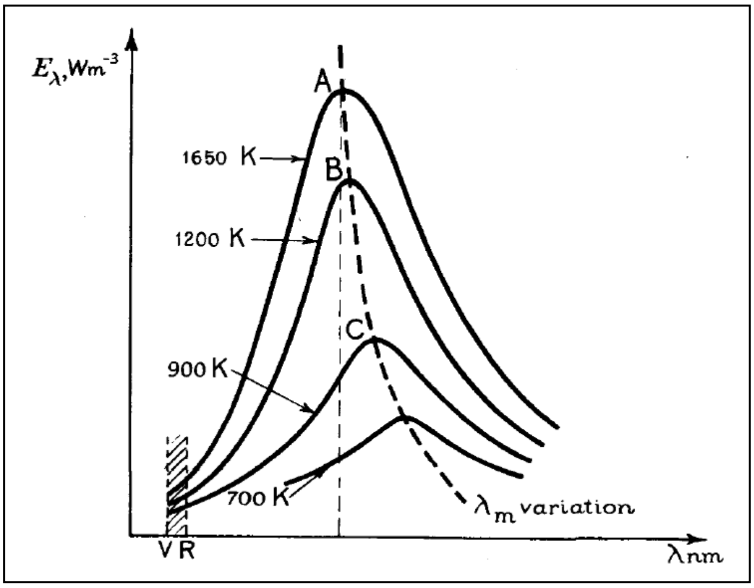
The precise underlying mechanism by which light was produced in the light source was not known exactly, but experiments showed that a hot body at a certain temperature T did not emit light with only one frequency f, but with different frequencies in the same time and that the intensity I of light at each frequency f was different.

Look at the results of such an experiment made by Lummer and Pringsheim for a body at a temperature of 1650 K in which the intensity of light was measured through its **heating effect** for each frequency [*Verhandlungen der Deutschen Physikalische Gesellschaft*, **2**, 163-180, 1890]:
(Note: The fact that the **intensity of light** was measured as a **heating effect** is a critical detail that will be discussed later.)

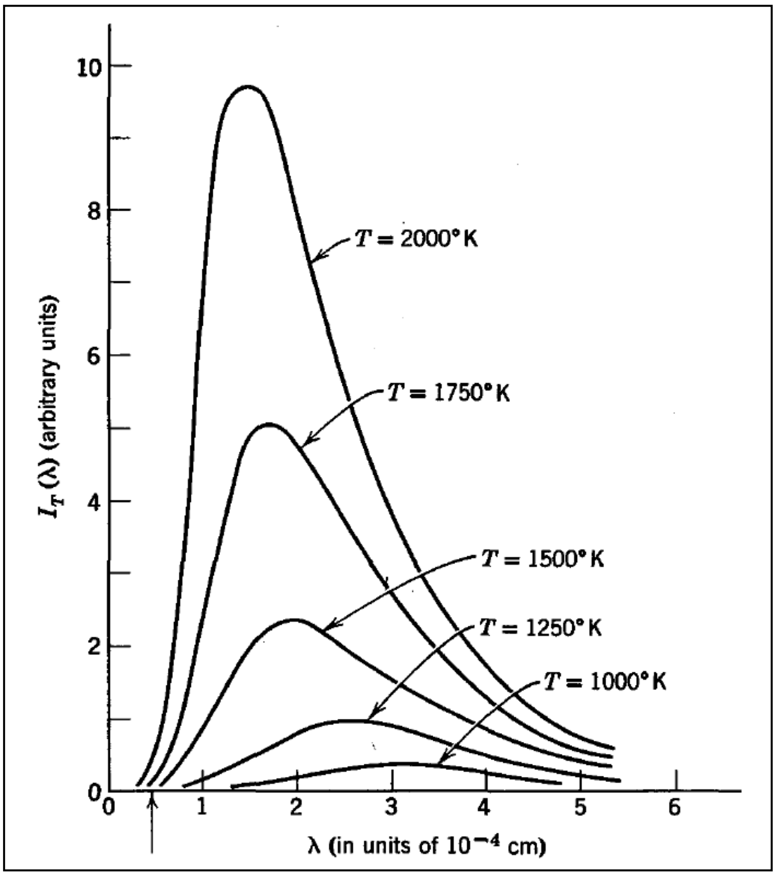


Observe that the intensity of the light emitted by the hot body does not have only one frequency (wavelength) but it is composed of a mixture of light waves of different frequencies f having different intensities.

If the temperature T of the hot body is decreased, the curve keeps the same shape but the total radiation (area under the graph) decreases and the maximum of intensity moves towards longer wavelengths (lower frequencies), in the figure below from A to B and to C [M. Nelkon, *Heat, A Textbook for Advanced Level in SI Units*, Blackie & Son, Limited, Glasgow (1978), p.188]:



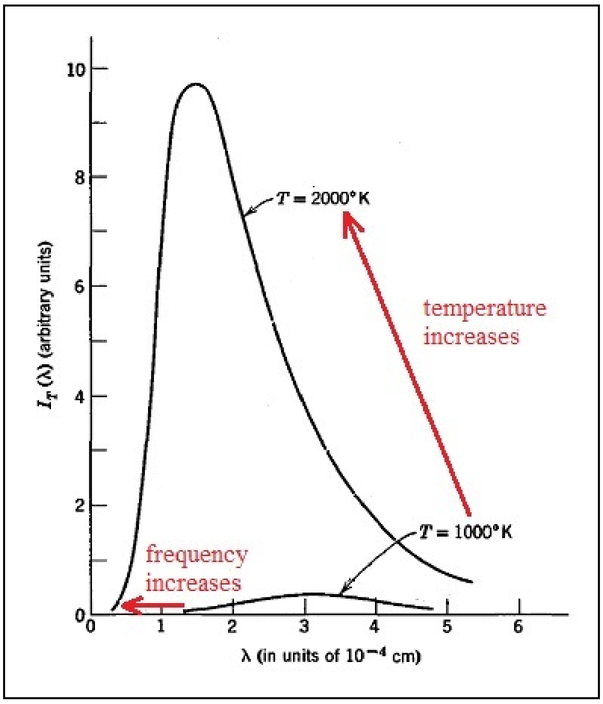
Similarly, if the temperature of the hot body is increased, the curve keeps the same shape but the total radiation (area under the graph) increases and the maximum of intensity moves towards shorter wavelengths (higher frequencies) [Robert Martin Eisberg, *Fundamentals of Modern Physics*, John Wiley & Sons, Inc., New York (1961), p.48]:



By looking at these graphs, we may ask today the same question that was asked when these graphs were obtained more than one hundred years ago:
What do they tell us about the mechanism of emission of light by a hot body at a temperature T?

There are a few very evident things that can be observed:

(i) at higher temperatures the cut-off of the graph moves towards higher frequencies (shorter wavelengths), as indicated in the figure below, based on the graphs shown above:

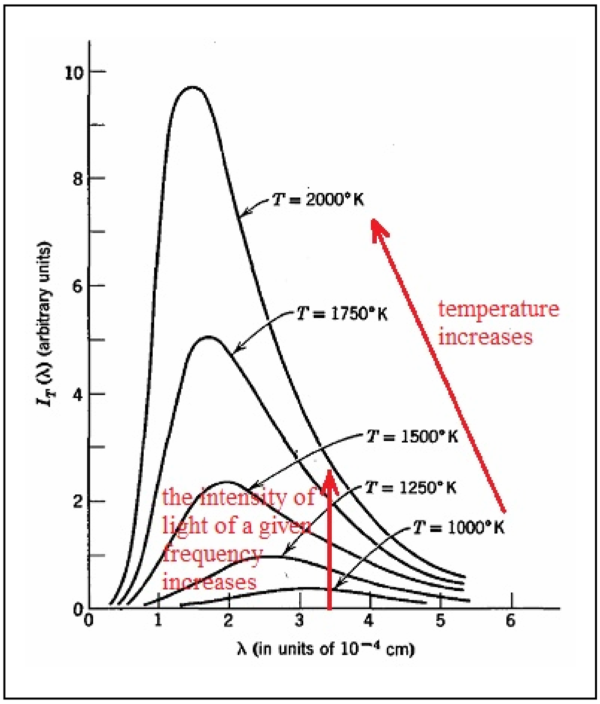


This tells us that the increase in the temperature of the hot body causes the atoms composing it to begin vibrating with higher frequency and thus emitting light waves of higher frequency.

But does it mean that, while doing so, they cease to emit light of lower frequencies?

The answer is no because:

(ii) the intensity of light of low frequency *does not diminish* with the increase in the temperature (it actually *increases* with the increase in the temperature), so the atoms that emitted light waves of low frequencies when at low temperatures continue to do so when at higher temperatures; this is indicated in the figure below:



From these two observations it can be said that the effect of increasing the temperature of a hot body is to cause the atoms composing it to begin emitting light of different frequencies *in the same time*.

However, the fact that the intensity of the light emitted at low frequencies *increases* with the increase in the temperature is startling: for if, when at higher temperatures, the atoms of the hot body simply began to emit light of higher frequencies while, in the same time, they continued to emit light of low frequencies as they emitted it when they were at low temperatures, the intensity at low frequencies *should have remained unchanged* and only the intensity at high frequencies should have increased with temperature.
Moreover, we observe that this increase of intensity occurs at *all* frequencies with increasing temperature, and that sometimes the increase is even ten-fold.
So what is going on? Can we explain this rationally, without introducing contradictory theories and postulates?

We will see below that we can.

But, before that, let us discuss another piece of evidence which, although **not essential**, helps us in understanding the situation we are looking at.

There is a very interesting and mathematically sound demonstration of the distribution of velocities among the particles forming a system: it is called Maxwell's statistical distribution and it was amply verified experimentally [I. Estermann, O. C. Simpson, O. Stern, *Phys. Rev.* ***71****, 238 (1947)*].
This distribution tells us that at higher temperatures there are, on the whole, more atoms with greater velocities. Below we will outline the main ideas just for reference.

Maxwell's original distribution function of velocities …

The number whose actual velocity lies between v and $v + dv$ is

$$N \frac{4}{\alpha^3 \sqrt{\pi}} v^2 e^{-\frac{v^2}{\alpha^2}} dv \ldots\ldots\ldots\ldots\ldots$$

[W. D. Niven (editor), *The Scientific Papers of James Clerk Maxwell*, Cambridge: at the University Press (1890), *Illustrations of the Dynamical Theory of Gases*, from the *Philosophical Magazine* for January and July (1860), p. 381]

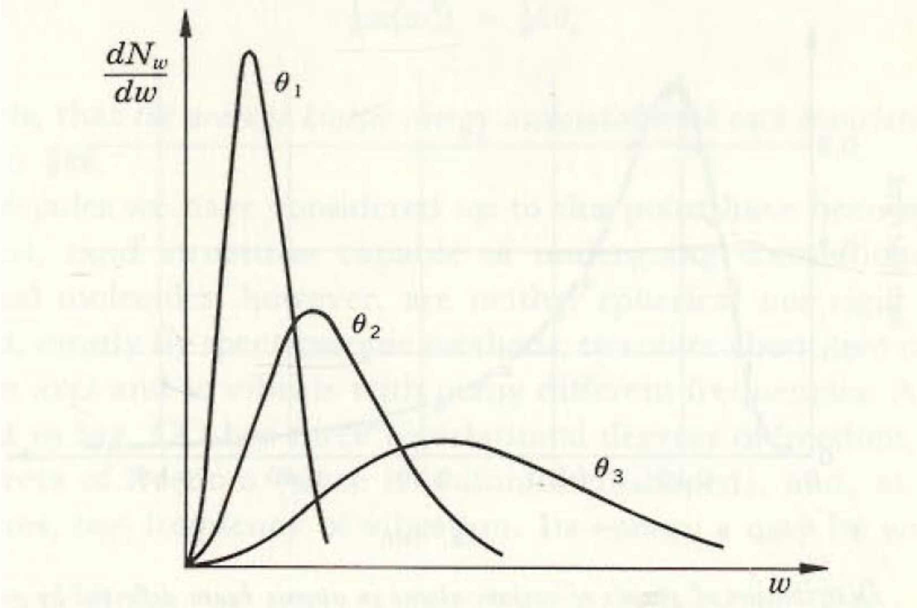
… can be rewritten as a function of temperature using thermo-dynamical arguments…

$$\frac{dN_w}{dw} = \frac{4N}{\sqrt{\pi}}\left(\frac{m}{2k\theta}\right)^{\frac{3}{2}} w^2 e^{-\frac{1}{2}mw^2/k\theta}$$

[Mark W. Zemansky, *Heat and Thermodynamics*, 5th Ed., McGraw-Hill Book Company (1968), p. 159]

… where θ is the absolute temperature T and w is the velocity of the particles.

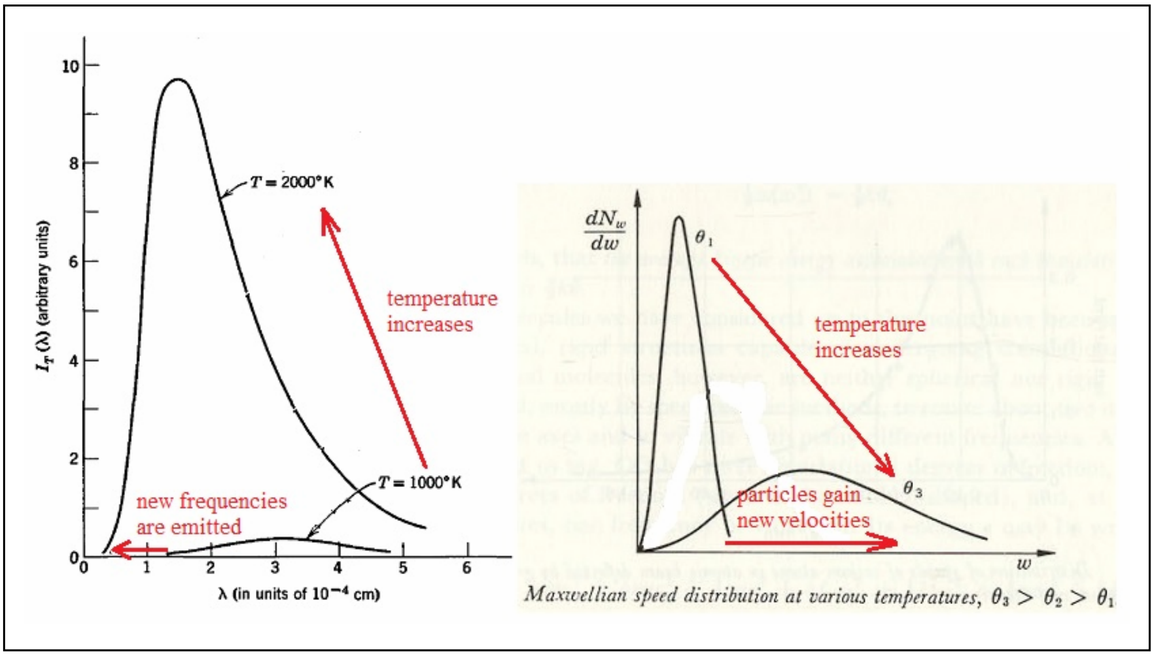
The plot of this function for different temperatures is shown below [Mark W. Zemansky, *Heat and Thermodynamics*, 5th Ed., McGraw-Hill Book Company (1968), p. 159]:



Maxwellian speed distribution at various temperatures, $\theta_3 > \theta_2 > \theta_1$

Observe that at higher temperatures there are, on the whole, more particles with great velocities than at low temperatures.

If we compare the radiation from the incandescent body and Maxwell's distribution, we cannot help to observe that there are some correlations. Look at the diagram below:



Firstly, observe that an increase in the temperature of the hot body brings about emission at new (higher) frequencies (left figure), while the distribution (right figure) tells us that at higher temperatures the atoms have greater velocities. This is consistent with the fact that at high temperatures the atoms emit more energy and do that at all frequencies because the intensity of light increases at all frequencies.

Secondly, observe in the distribution the situation at low velocities: there are many more atoms with low velocity at low temperatures than at high temperatures; however, the intensity of light of lower frequency -the range in which the atoms emit when at low temperatures- is higher at high temperatures than at low temperatures: this is a clear indication that at high temperatures atoms with greater velocities must be contributing to the spectrum with radiation of low frequency. But even if we consider that they all contribute like they did when they had low velocities at low temperatures, it is not enough to explain the three-fold (sometimes even ten-fold) increase of the intensity of light of low frequencies at high temperatures.

So this brings us back to our question: can we explain this increase in the intensity at low frequencies (and indeed at all frequencies) rationally, without introducing contradictory theories and postulates?

Yes, we can, if we admit that atoms when at higher temperatures, while beginning to vibrate at higher frequencies, not only that continue to vibrate at low frequencies, but develop *new modes* of vibration at low frequencies – in this way more radiation of low frequency is emitted by the same number of atoms. These *new modes* of vibration can be, for example, simultaneous vibrations of the atom along different directions of space.

Another possibility is to suppose that the amplitude of their vibration at low frequencies has increased, thus increasing the intensity of radiation emitted. This is, however, not plausible because:

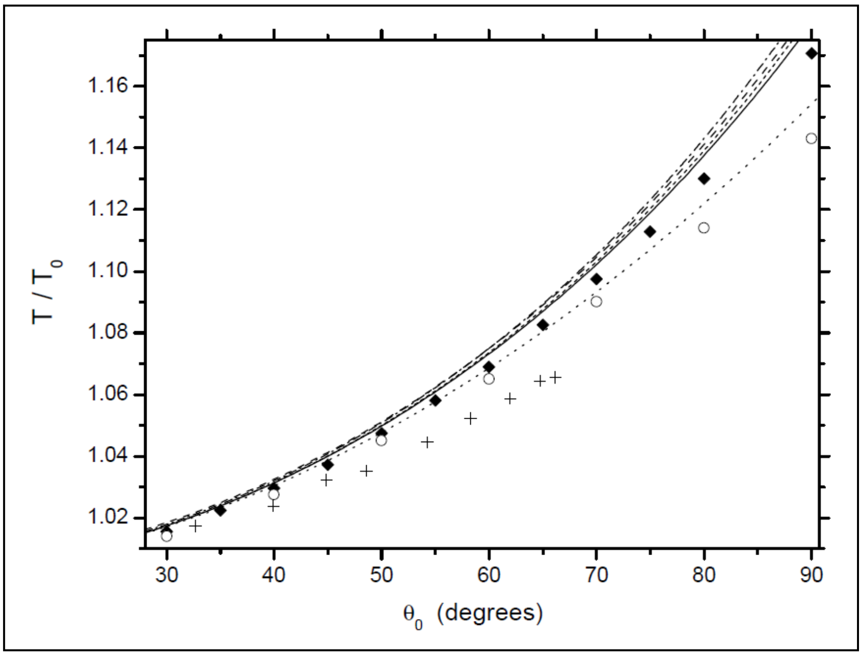
- there is no reason to assume that atomic vibrations are *isochronous*, i.e. that the amplitude of vibration does not depend on the frequency of vibration, since this would imply that the forces involved in vibrations are proportional with the displacements and it is known that the atomic forces are electrostatic, depending on the inverse square of the distance.
- we do not have, even in the macroscopic objects around us, any example in which the frequency of vibration is *strictly* and *genuinely* independent of amplitude: the simple pendulum for example, when solved exactly, gives a very complicated (non-analytical) dependence of the period of oscillation T (frequency f is f=1/T) with the amplitude of oscillation θ_0 [F.M.S. Lima, P. Arun, *An accurate formula for the period of a simple pendulum oscillating beyond the small-angle regime*, Am. J. Phys. 74 (10), 892 (2006)]:

$$T = 4\sqrt{\frac{L}{g}} \int_0^{\pi/2} \frac{d\varphi}{\sqrt{1-k^2 \sin^2 \varphi}}$$

where

$$k \equiv \sin\left(\theta_0/2\right)$$

The plot of this function is shown in the graph below (solid line):



Another example is the mass-spring system in which the force is taken to obey Hooke's law and thus proportional to displacement; since the force is an approximation of the attractive and repulsive forces acting between the atoms of the spring, about which we know that are also electrostatic in nature, we can see that the proportionality is not *strictly* true.

The conclusion is therefore that the atoms in a hot body acting as a source of light vibrate at many frequencies at the same time, develop *more modes* of vibration at a given frequency the higher their energy, and the amplitudes of their vibration changes with the frequency.
That this is so can be seen from the formula for the maximum velocity in simple harmonic motion along one direction in space $v_{\max} = 2\pi f \cdot A$: if the amplitude A and the frequency f remain the same, higher maximum velocity $v_{\max}$ of the oscillator will only be possible if the oscillator develops new modes of vibration, in other directions of space.

So why is this discussion helpful or relevant to the topic of the photoelectric effect?

1. The purpose is to show that, even if a quantitative (mathematical) proof is not provided, all the experimental observations can be explained simply by employing known principles, namely that atoms emit light waves through their vibration, being not only unnecessary but also inadequate to claim that atoms emit "particles of light" (photons). Not knowing the exact structure (and even shape) of the atoms (or of their bonds, which may also vibrate and emit light waves) is an impediment in the study of the atomic modes of vibration and in finding a correct mathematical equation that explains the curves of radiation of hot bodies. Theoretical studies of the modes of vibration of a hard sphere have probably started from this necessity [H. Lamb, *On the Vibrations of an Elastic Sphere*, Proc. London Math. Soc. (1881) s1-13 (1): 189-212].

If light is somehow **quantized** it is *not* because the nature of light is that of a particle but because the light wave comes from an atom, which is a discrete entity; we may thus draw the conclusion that what we call **photon** is not a particle but the continuous wave emitted by **one atom** at a certain frequency – and we will see that this picture fits very well in the explanation of the photoelectric effect as an effect of electromagnetic induction.

Thus, a physical light source, which is a substance composed of atoms which all vibrate and emit light waves, emits light composed of a great number of waves produced by its vibrating atoms.

2. We can see that one is not justified in claiming that, when the intensity of light of a given frequency has increased, the “amplitude of the light wave” has increased.

Firstly, because, being composed of so many elementary waves, the light of a given frequency produced by a light source is not only “one wave”, so we cannot speak about the “amplitude of the light wave”.

Secondly, if we refer to the amplitudes of the elementary waves composing the light emitted by a light source, we have seen that we can consider them equal for a given frequency and thus obtain that what we call the intensity of light is in fact proportional to the number of elementary sources (atoms) emitting it multiplied by the square of the amplitude of one of the elementary waves emitted, since all have equal amplitudes:

$$I \propto N_f \cdot A^2 .$$

3. Then what about the experiments discussed above on the measurement of the radiation of hot bodies? Is it correct to claim that a *change* ΔI in the intensity of the same radiation corresponds to a change ΔA in the “amplitude of the light wave” (since the intensity of a wave proportional to the square of its amplitude $I \propto A^2$)?

It is true that the intensity of a wave is proportional to the square of its amplitude but, as we have discussed above, light coming from the light source does not contain only *one* wave: since the intensity I of the light of a certain frequency f coming from the source is proportional to the number N_f of atoms vibrating at that frequency and to the square of the amplitude of vibration of one wave,

$$I \propto N_f \cdot A^2$$

a *change* ΔI in the intensity of the same radiation does **not** correspond to a change ΔA in the amplitude A of the waves (since we have seen that atoms vibrating at a given frequency do so with a constant amplitude) but to a change in the number N_f of atoms emitting at that frequency f:

$$\Delta I \propto \Delta N_f \cdot A^2 .$$

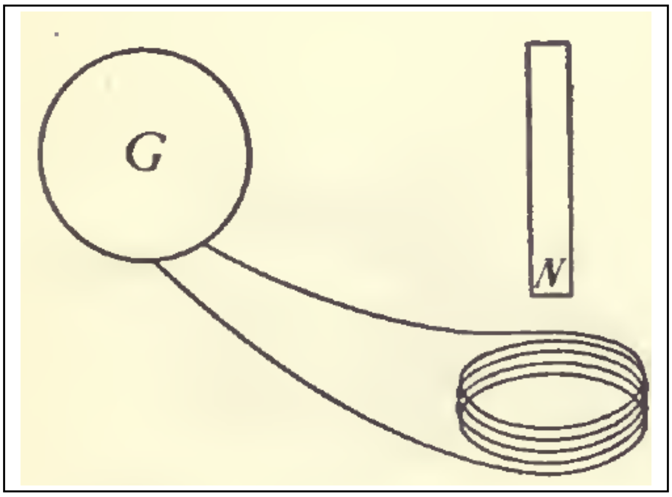
In this section we have seen that an atom does not emit photons but continuous waves of different frequencies. When these waves, magnetic in nature, fall on the surface of a metal expel electrons from that metal. I stated that this emission of electrons occurs through electromagnetic induction. So before discussing the experimental observations of the photoelectric effect proper, let us take a fresh look at Faraday’s effect of electromagnetic induction.

C. A *novel* look at Faraday's effect of electromagnetic induction: When a magnet is inserted in a coil, what does the changing magnetic field of the magnet induce in the coil, an electric field or an electric current?

I have answered the question posed above in Part I of this series on Radio Waves where I have shown that the present formulation of Faraday's law claiming that the moving magnet induces in the coil an electric field (and a corresponding emf) is an assumption without experimental support.

Let us take a *novel* look at the effect of electromagnetic induction by referring strictly to what experiments show. The following three observations can be made by anyone having a loop of metallic wire, a sensitive galvanometer (that measures the intensity of the electric current) and a bar magnet:

<u>Observation ONE</u> A moving magnet induces (produces) an *electric current* in a loop of wire, as shown in the diagram below:
[figure taken from Willis E. Tower, Charles H. Smith and Charles M. Turton, *Physics*, P. Blakiston's Son & Co., Philadelphia (1920), p.327]



<u>Observation TWO</u> Moving the magnet *faster* increases the intensity of the induced electric current.

<u>Observation THREE</u> A *stronger* magnet moved at the same rate increases the intensity of the induced electric current.

Again, we may ask ourselves the same questions that were asked almost two hundred years ago when this effect was discovered:

Q1. What really happens in the metal of the loop of wire when the current is produced by the moving magnet?
and
Q2. Why does the induced current increase in the manner described in observations TWO and THREE?

We can answer these questions if we recall that the intensity of the electric current is given by the total electric charge passing a point of the circuit in unit time

$$I = \frac{Q}{t},$$

and, knowing that these charges are electrons (Faraday did not know this at his time), we obtain the following formula for the intensity of the electric current

$$I = \frac{N \cdot e}{t} = \frac{N \cdot e \cdot v}{l},$$

where N the number of moving electrons, l the length of the wire, e the charge of the electron and v the velocity of electrons).

This last equation gives us the answer the question Q1 above: in electromagnetic induction an electric current is produced because a certain *number N of electrons* are caused to move with a certain *velocity v*.

Question Q2, however, cannot be answered unambiguously, because there are *two* possibilities: a *magnet moving faster* may be considered to cause either the *number* N of moving electrons to increase or the *speed* v of electrons to increase; in the former case a stronger magnet moving at the same rate will cause the electrons to move faster, in the latter it will cause more electrons to move at a certain speed.
These two possibilities can be summarized in a table as below:

Induced current is proportional to N and v		
	Magnet Rate increases (Strength constant)	Magnet Strength increases (Rate constant)
Possibility 1	N	v
Possibility 2	v	N

How can we discriminate between these two possibilities?

The only direct way would be to interrupt the wire of the loop, form a gap and measure how the number N of electrons and their velocities v through the gap change with the

movement and the strength of the magnet. This would imply, ironically, the emission of electrons from one side of the gap and their travel to the other side of the gap, which could be done if we place the respective gap in a glass tube in high vacuum.
Such an experiment would indeed be an *experimentum crucis* for our investigation of the photoelectric effect; however, we can will proceed with our reasoning in reverse order and **use the photoelectric effect to settle this issue**.
Thus, in the absence of the *experimentum crucis* mentioned above, we will anticipate the laws of photoelectric effect that will be discussed in the next section and state that these laws point out towards Possibility 2, that a magnet moving faster increases v (it will cause the electrons to move faster) and that a stronger magnet increases N (it will cause more electrons to move). We can further state the following conclusions:
(α) The fact that the number of electrons N caused to move in electromagnetic induction increases with the strength B of the magnet, points to the conclusion that B and N might be proportional: $B = N \cdot b$, where b would correspond to the minimum magnetic field strength necessary to cause an electron to move (I will call b *teslon*).
(β) We can state, again anticipating the laws of the photoelectric effect, that, based on the observation that in electromagnetic induction a magnet moving faster increases v, the exact relationship between the velocity v gained by the electron due to the change of magnetic field is given by the equation $v^2 = k \cdot \frac{dB(t)}{dt}$, where k is a constant.

With these two conclusions we are ready now to discuss the quantitative observations of the photoelectric effect:

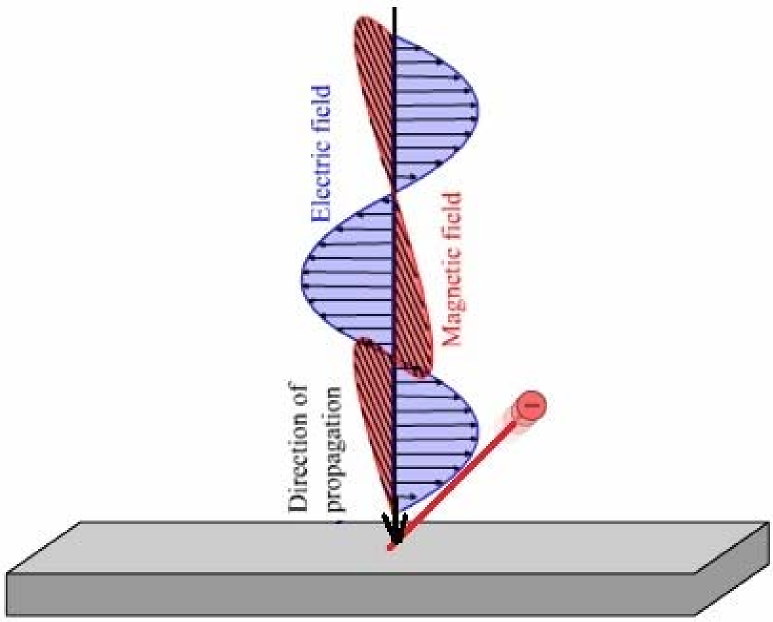
I will comment on what was wrong in the attempted explanation of this effect in terms of the wave theory of light because it was due to wrong assumptions and arguments that the wave theory of light was dismissed as a whole and the particulate theory of light accepted.

I will also show what should have been the correct interpretation of the photoelectric effect in terms of the wave theory of light that gives consistent and meaningful explanations of the observed phenomena, thus showing that the hypothesis of the existence of “particles of light” was not only unnecessary but also inadequate.

D. The quantitative observations of the photoelectric effect and their interpretation as a phenomenon of electro-magnetic induction

In this section I will discuss the experimental findings based on the observations of the photoelectric effect and show that, due to misapplication of the wave theory of light, to the insufficient understanding of the mechanism of emission of light by light sources, and to the confusion of the mechanisms of energy transfer in heat and photoelectricity, the scientists of the past erroneously declared that the photoelectric effect cannot be explained with the wave theory of light and erroneously claimed that the whole picture of light as a wave breaks down at the microscopic (atomic) level, dropping it altogether and replacing it with a "particulate", "quantized" theory of light purporting that light is a stream composed of light-quanta called "photons".

The most obvious erroneous assumption in the old attempt to explain the photoelectric effect by the wave model was the claim that the electron is acted on by the electric field of the light wave. Look at the figure below to see the inconsistency:



Observe that the electric field of the light wave oscillates parallel to the metal surface.
How can an electron forced to move parallel to the surface exit perpendicular to it?

On the other hand observe that, if we consider how the electrons should move if they were ejected through electromagnetic induction by the varying magnetic field of the light wave (which acts also parallel to the surface of the metal), we obtain that the electrons can either be driven deeper in the metal or out of it.
This inconsistency and **Observation ONE**, discussed below, were the first to suggest to me that the photoelectric effect is caused by a changing magnetic field and therefore it is an instance of Faraday's effect of electromagnetic induction.

Observation ONE There is a linear relation between the retarding potential that stops the photoelectric current emitted from a surface and the frequency of the light falling on that surface

This is expressed in the equation $hf = \frac{mv^2}{2} + W$ mentioned in the abstract of this work.

The original experimental equation was $hf = eV_{stopping} + W$ or, more correctly $\frac{h}{e} f = V_{stopping} + \frac{W}{e}$ because in experiments not energies are measured or controlled, but voltages.
Nevertheless, the stopping potential $V_{stopping}$ does correspond to the term $\frac{mv^2}{2}$ because the latter is the maximum kinetic energy of an electron expelled from the surface without losing energy through collisions on its way out of the metal and it is measured from the stopping potential $V_{stopping}$, which is the retarding potential difference needed to stop an electron with this highest kinetic energy $\frac{mv^2}{2}$(if a potential can stop one of these most energetic electrons it can also stop *all* of them and it can stop also *all* the electrons with less kinetic energy than this; so the stopping potential stops all the photoelectric current).
The energy lost (or gained) by an electric charge q traveling in a retarding (respectively accelerating) potential difference V is equal to qV so, if an electron with the kinetic energy $\frac{mv^2}{2}$ is to loose all of its energy and come to rest, it must travel in a retarding potential difference $V_{stopping}$ that satisfies the relationship $\frac{mv^2}{2} = eV_{stopping}$, where e is the electric charge of the electron.

The experimental setup is shown below left, the same as the one shown previously in section A [Arthur Beiser, *Concepts of Modern Physics*, 2nd Ed., McGraw-Hill Kogakusha, Ltd. (1973), p. 44]; below right are the observations when the illuminated electrode is aluminium [Arthur Llewelyn Hughes and Lee Alvin DuBridge, *Photoelectric Phenomena*, 1st Ed., McGraw-Hill Book Company, Inc., (New York and London, (1932), p.18-19]:

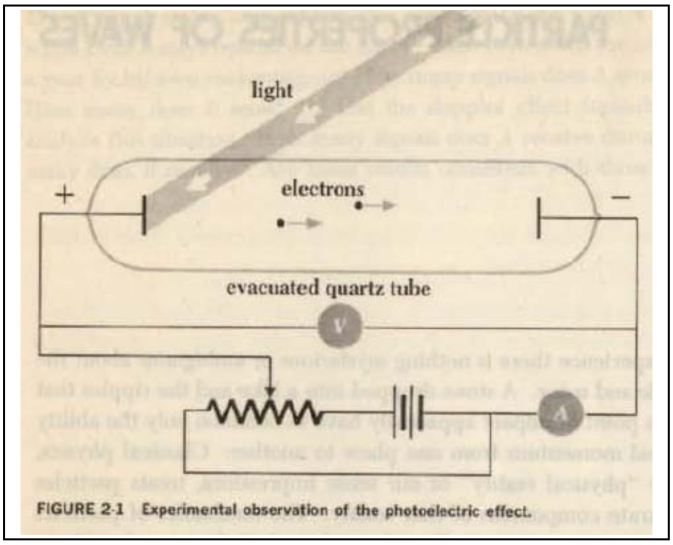
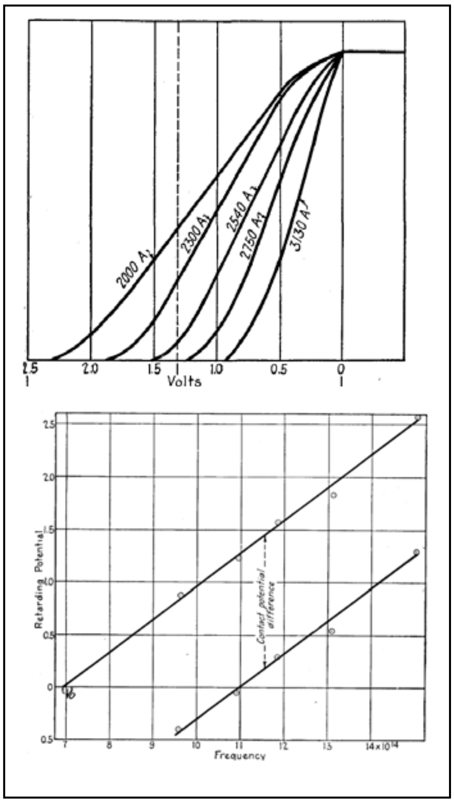


FIGURE 2-1 Experimental observation of the photoelectric effect.



Observe that to every wavelength (frequency) there is a retarding voltage for which the photoelectric current becomes zero – this is the stopping voltage $V_{stopping}$ which, when plotted against frequency, gives a straight line. The gradient of this line can be found from the graph and comes out equal to the ratio h/e (the ratio of Planck's constant h to the charge of the electron e): $\frac{h}{e} = \frac{6.67 \cdot 10^{-34}[m^2kgs^{-1}]}{1.6 \cdot 10^{-19}[C]} = 4.13 \cdot 10^{-15}[Wb]$.

The observation that the stopping potential $V_{stopping}$ is proportional to the frequency f of the light was one of the first in which the wave theory of light was misapplied because it was supposed that the energy of the electrons ejected from the metal came from the energy of the light wave which acted on the electron through its changing *electric field*; it was believed that, since the intensity of the light wave is proportional to the square of the amplitude of its *electric field* and is *independent* of frequency, the stopping voltage $V_{stopping}$ should be dependent *not* on the frequency of the light but on its intensity only.

This misinterpretation, as all the others to be discussed here, was due to the fact that the **mechanism** by which the transfer of energy from the light wave to the electron took place was not understood and to the misconception, discussed at large in the previous section, that the intensity of light emitted by a light source at a given frequency is proportional only to the square of the amplitude of the wave and not also to the number of atoms emitting it.

On the other hand this was one of the observations that strongly suggested to me that the photoelectric effect is an instance of electromagnetic induction occurring at the surface of a metal.

For if $V_{stopping}$ is the potential necessary to prevent an electron from leaving the metal surface illuminated with light of frequency f, and if this photoelectron is in the first place produced through electromagnetic induction gaining a velocity v whose square is proportional to the rate of change of the magnetic field of the light wave $B(t) = B_0 \sin(2\pi \cdot f \cdot t)$, then the equality of energies

$$\frac{mv^2}{2} = eV_{stopping}$$

and $v^2 = k \cdot \dfrac{dB(t)}{dt}$

yield

$$v^2 = k \cdot \frac{d[B_0 \sin(2\pi \cdot f \cdot t)]}{dt} = k \cdot B_0 \cdot 2\pi \cdot f \cdot \cos(2\pi \cdot f \cdot t)$$

and the stopping potential

$$V_{stopping} = \frac{m}{2e} \cdot k \cdot B_0 \cdot 2\pi \cdot f \cdot \cos(2\pi \cdot f \cdot t)\,.$$

The stopping potential must be equal to the maximum value of $\dfrac{m}{2e} \cdot k \cdot B_0 \cdot 2\pi \cdot f \cdot \cos(2\pi \cdot f \cdot t)$, which obtains when $\cos(2\pi \cdot f \cdot t) = 1$.

The final value for the stopping potential is then

$$V_{stopping} = \frac{m}{2e} \cdot k \cdot B_0 \cdot 2\pi \cdot f = F \cdot f\,,$$

from which we observe at once that the stopping potential $V_{stopping}$ **is proportional to the frequency f of the light falling on the metal surface of the photoelectric tube**.

Recalling that $B_0 = N \cdot b$, and that we are discussing the situation of one electron, the constant of proportionality F is equal to $F = \frac{m}{2e} \cdot k \cdot b \cdot 2\pi$ and, from comparison with the experimental findings, it should have a value comparable with the constant h/e, where h is Planck's constant and e is the charge of the electron.

Observation TWO The retarding potential that stops the photoelectric current does not depend on the intensity of the light

This follows from the above calculations showing that the constant F does not depend on the amplitude $B_0 = N \cdot b$ of the wave.
Physically this corresponds to the fact that when B_0 changes the number N of electrons caused to move through electromagnetic induction changes. Moreover, the method used for changing B_0 is not relevant: changing the distance between the light source and the illuminated metal surface, changing the temperature of the hot body acting as a light sources, or changing the aperture through which light is admitted in the photoelectric tube will lead to the same effect of changing the number of electrons moving and not their velocities.

Observation THREE There is a frequency of light (called threshold frequency f_0) below which the photoelectric effect does not occur; this threshold does not depend on the intensity of light

This can be seen in the plot shown at Observation ONE, where the stopping voltage becomes zero at a frequency $f_0 = 7 \cdot 10^{14}\,Hz$ for aluminium.

Here it was claimed in the past that the wave theory of light fails altogether because electrons can gain enough energy from the *electric field* of the light wave if the intensity of the light is increased enough, so the frequency can be as low as possible, without any threshold.

As discussed above, this misinterpretation is due to lack in the understanding of the **mechanism** by which the transfer of energy wave-electron occurs. If the photoelectric effect is seen as an effect of electromagnetic induction the existence of a threshold frequency is not at all surprising since the atom of the electrode has a minimum ionization potential and this is so even when it is in the lattice of a metal (the ionization

potential is expressed as an energy in this case and called work function W).
If the frequency of radiation is below the threshold frequency f_0, the electron does not gain enough speed to escape from the attraction of the metal, its energy is below that of the work function W, and no photocurrent can be obtained.
Even if the light intensity is increased no photocurrent will be produced at frequencies $f < f_0$ since the intensity is given by the amplitude of the wave $B_0 = N \cdot b$, which means that not more energetic, but a greater number of electrons will be caused to move (recall that this is as a consequence of the interpretation of Faraday's effect of electromagnetic induction discussed in the previous section).

Observation FOUR The photoelectric current is proportional to the intensity of light

This was not used as a serious objection to the wave theory of light, but rather as a support for the "particulate" theory of light and it assumed that a "photon" would eject an electron so light of greater intensity, which meant more photons in unit time, would eject more electrons in unit time producing a photoelectric current of greater intensity.

On the other hand, again due to the lack in the understanding of the **mechanism** by which the transfer of energy wave-electron takes place, the wave theory was said to give ambiguous predictions because the number of electrons released by the light wave in unit time may be proportional either to the *amplitude* of the electric field, or to the *square of the amplitude* which is a measure of the intensity; in the latter case the wave theory would gave a correct explanation, in the former no, since the intensity of the photoelectric current would come out proportional to the square root of the intensity of the light. However, no serious theory was advanced, which comes to show again that the subject of the photoelectric effect was dealt with very superficially in those times.

That the photoelectric current must be proportional to the intensity of light comes as a natural consequence if the effect is explained as electromagnetic induction. For greater intensity implies either more atoms vibrating in the source of light at the same frequency and amplitude so more waves emitted or simply greater amplitude of the wave emitted by each atom (if the distance to the source of light is decreased); the former will cause more interactions between waves and electrons, the latter more electrons to move under the action of one wave, both resulting in a photoelectric current of greater intensity.

Observation FIVE The emission of electrons starts immediately when the surface is illuminated

This can be easily explained since, as discussed in Observation ONE, the electrons are caused to move deeper in the metal half of the period and out of the metal during the other half period. Considering the frequencies of the UV light in the order of $10^{15}[Hz]$, the magnetic field of the wave would oscillate with a period $T = \frac{1}{f} = 10^{-15}[s]$ during half of which electrons would be released from the surface. Such a small interval of time does indeed mean that there is no perceptible time lag between the shining of light and the detection of photoelectrons.

The quantum theory of light explains this as due to the collisions of the "light particles" with the electrons of the irradiated metal without offering any details as to how the collisions cause the electron to be ejected from the metal surface.

Conclusion

In conclusion, in the present article I have tried to show how the wave theory of light can give reasonable explanations of the photoelectric effect if this effect is considered an effect of electromagnetic induction in which electrons are expelled from the atoms at the surface of a metal under the action of the changing magnetic field of the incident light wave.

The previous attempt, made one hundred years ago, to explain the photoelectric effect by the wave model failed mostly because the electrons were believed to be acted on by the electric field of the light wave, i.e. through a kind of electrical forced oscillations.

The difficulties encountered in those times are summarized in the modern textbooks published today, of which one example is the table below, taken from David Sang, Graham Jones, Richard Woodside and Gurinder Chadha, *Physics*, Cambridge University Press, (2010), p. 439:

Observation	Wave model	Photon model
Emission of electrons happens as soon as light shines on metal	Very intense light should be needed to have immediate effect	A single photon is enough to release one electron
Even weak (low-intensity) light is effective	Weak light waves should have no effect	Low-intensity light means fewer photons, not lower-energy photons
Increasing intensity of light increases rate at which electrons leave metal	Greater intensity means more energy, so more electrons released	Greater intensity means more photons per second, so more electrons released per second
Increasing intensity has no effect on energies of electrons	Greater intensity should mean electrons have more energy	Greater intensity does not mean more energetic photons, so electrons cannot have more energy
A minimum threshold frequency of light is needed	Low-frequency light should work; electrons would be released more slowly	A photon in a low-frequency light beam has energy that is too small to release an electron
Increasing frequency of light increases maximum kinetic energy of electrons	It should be increasing intensity, not frequency, that increases energy of electrons	Higher frequency means more energetic photons; so electrons gain more energy and can move faster

Observe how the particulate theory of light was accepted due to the inability of the wave theory to explain the observed phenomena.

On the other hand, in this article I have pointed out that, through an adequate interpretation of Faraday's effect of electromagnetic induction, all the observations made on the photoelectric effect can be accounted for. This is summarized in the following table:

	Observation	Wave model (old)	Wave model (electromagnetic induction)
1	Emission of electrons happens as soon as light shines on metal	Very intense light should be needed to have immediate effect	Electron velocity points out of the surface during half the period of a wave which is of the order of $10^{-15}[s]$; this is fast enough to not perceive any delay between the shining of light on the metal surface and the expulsion of electrons
2	Even weak (low-intensity) light is effective	Weak light waves should have no effect	Weak light will still act on an electrons and produce photoelectrons; however, <u>there is</u> a minimum value b (*teslon)* for the magnetic field strength of the wave that can act on one electron and cause it to move.
3	Increasing intensity of light increases rate at which electrons leave metal	Greater intensity means more energy, so more electrons released	Greater intensity means more waves or greater amplitude $B_0 = N \cdot b$, and both lead to an increased number of electrons acted on through electromagnetic induction.
4	Increasing intensity has no effect on energies of electrons	Greater intensity should mean electrons have more energy	Greater intensity means more waves or greater amplitude $B_0 = N \cdot b$, while the velocity gained by one electron through electromagnetic induction is $v^2 = k \cdot \frac{db(t)}{dt}$ so independent of the total amplitude of the wave.
5	A minimum threshold frequency of light is needed	Low-frequency light should work; electrons would be released more slowly	Low-frequency light does not cause an electron to gain a velocity great enough to be expelled from the metal since

			$v^2 = k \cdot \frac{db(t)}{dt}$.
6	Increasing frequency of light increases maximum kinetic energy of electrons	It should be increasing intensity, not frequency, that increases energy of electrons	Increasing the frequency increases the velocity gained by one electron through electromagnetic since Faraday's effect of electromagnetic induction suggests that $v^2 = k \cdot \frac{db(t)}{dt}$

-- End of Paper --