Concerning Hertz’ photoelectric effect

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March 31, 2022

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Keywords: photoelectric effect, Maxwell-Hertz electromagnetic theory, detected signal
PACS: 34.10.+x, 03.50.Kk, 84.47.+w,

Abstract

Experimental evidence of the photoelectric effect goes back to H. Hertz. It occurred during the famous confirmation experiments of the Maxwellian theory. It is commonly held however that it cannot be explained in the framework of that theory. We are calling attention to some aspects linked with the interpretation of that effect on which, in our opinion, it is worthwhile reflecting.

Introduction

As known, in 1905, in addition to the theory of relativity and a kinetic treatment of Brownian movement, A. Einstein proposed a heuristic explanation of the photoelectric effect. We see in this proposal at least two original choices.

In the first place, in the 1905 work Einstein takes up a hypothesis of M. Planck, new and anything but accepted; it is he who will elucidate the innovative content thereof. The hypothesis reproposed admits that upon thermodynamic equilibrium light be emitted and absorbed by matter only in discrete quantities, the so-called quanta. The innovative content of the hypothesis concerns energetically corpuscular constitution of light if we may express ourselves thus.

In the second place, he applies this hypothesis, and hence the theory in whose framework it is formulated, to a curious behaviour of metals and gives a simple explanation thereof. The experimental analysis of the effect on which he bases himself is P. Lenard’s.

Today, the experiments of R. Millikan are taken as confirmation beyond a doubt of that theoretical hypothesis. It seems that, at the most, physics will try to improve the fits of foresight of the numerical values sanctioned therewith.
Here we would like to draw attention to the fact that no experiment verifying equations necessarily proves the correctness of a general theory. Admitted that a theory is sufficiently general and logically coherent, it suggests but does not guarantee a relationship between observed facts. Another theory, based on equally rigorous mathematics, could lend itself to connecting very similar facts in a manner at all different. We shall seek to show how this takes place in a specific case. That is to say we see how electromagnetism explains the photoelectric effect. We believe indeed that just this effect supplied H. Hertz with the key for testing Maxwell’s theory experimentally.

**Relationship of photoelectricity to electromagnetism**

The photoelectricity explained by Einstein pertains to the electrical behaviour of specifically irradiated metallic bodies. This is a physical fact, i.e. an observed fact, of which an objective description can be given. Under well defined experimental conditions it is reproducible.

Electromagnetism is a theory. Several theories have been proposed to account for electrical and magnetic phenomenology and Maxwell debates it in his treatise [1]. The theory which we understand is his, i.e. the one summarized in the equations which bear his name. According to his intentions this theory accounts for the electrical facts observed by M. Faraday. Electromagnetism is notoriously also one of the theories of light phenomena.

Electromagnetism is a good theory if it is coherent and if it accounts for the physical facts for which it was written.

Verification of coherence is the duty of mathematical logic. *As an alternative*, especially in physics, coherence has been proven by recourse to a model or construction of one. In this case the model places the observed facts in a certain relationship. In addition to substituting (partially) the logical reduction, it can act as a link for the physical explanation.

In this work we take for granted that Maxwell’s linear equations allow development of a coherent general theory and we concern ourselves with the electromagnetic explanation of the photoelectric effect. Disregarding interpretative preferences, those who believe the electromagnetic theory insufficient or inadequate for explanation rule out this effect’s being related to those allowed for by Maxwell or even repute that the incorporation of one more law formulated in such a manner as to characterize the phenomenon would make the theory incoherent.

Our point of view on the question being stated, we propose to trace the phenomenon most similar to the photoelectric effect which Maxwell surely considered again. For this purpose we state specifically that the paternity of the photoelectric effect is not attributed to P. Lenard but to H. Hertz.

Lenard [14] writes, “the action of ultraviolet light [on metallic surfaces] was discovered by Hertz. Hallwachs was the first to show that there is a simple relationship [of UV lighting] with extraction of negative electricity [from the volume] of bodies. Today that relationship is well studied”. The experiment
concerns current through a phototube when the cathode is irradiated.

Hertz writes [9], “Fast electrical movement excitation experiments being initiated I noticed an interaction [between emitting RLC and receiving RLC] which caused simultaneous release of sparks [between the facing capacitor spheres. . . . ] For some time I asked myself if I hadn’t run into a new form of electricity capable of interacting at a distance. […] The phenomenon was later investigated by Righi, Hallwachs, Elster and Geitel; a satisfactory explanation of the mechanism is still lacking”. The experiment concerns metallic reflection in the UV.

Since by scientific convention the same effect is concerned [11], to say the least it is not characterized by detection with the electrometer of the convection current emitted. In Hertz’ work indeed all mention of measurement of a current is lacking. So let us leave aside consideration of the mathematical expression for the electrical responsivity of the irradiated metallic surface and let us observe that photoelectricity is enumerated among electrical oscillation resonance phenomena. Those experiments were designed to prove or confute Maxwell’s theory and they proved it.

It seems to us that the circumstance of confirmation presupposes some convergence of the observations of Hertz and those made previously by Faraday. Faraday’s electrical research was centered on transmission. Moreover, it is rich with insights into phenomenology, even spectacular, of metallic surfaces; His work also contains a crop of observations on the behaviour of dielectric materials called theretofore electrical insulators. When the author concerns himself with transmission through the air he distinguishes the spark release before closing of the electrical contact in the mercury switch from the one released when the contact is broken. The second fact was called by him ‘self-induction’. The first [6], described as a fast conduction trigger without metallic contact and without arc formation, is attributed by him to a tension state dependant on the chemical-physical conditions of the metallic surfaces involved. Both mean that the purple part of the band is transmitted between the metals in the ‘tension state’ without the need of an antenna. Naturally Faraday knew nothing about antennas.

After Hertz, Lenard and especially Millikan, tended to exclude the contribution of reflection to the current, treating the metallic surfaces of the electrodes in such a manner as to make them nonspecular. They can, for example, be blackened and in this case it again depends on to what degree of blackening one wishes to refer the photoelectric effect on the underlying metal. Lenard speaks almost immediately of the photoelectric effect of retort carbon irradiated with the carbon arc [13].

Although the application capacity varies considerably, the difference between pulse propagation in a dispersive medium and transmission of a modulated carrier in a range of frequencies such that the behaviour of the air approaches vacuum does not affect the possibility of electromagnetic representation. Thus it seems that Maxwell’s theory should lend itself to some linear schematization of the photoelectric effect.
Modeling interpretation of the radiation-matter interaction

In the previous paragraph we separated the problems of mathematical coherence from those linked to the plausibility of interpretation. We mentioned that in a physics theory the model serves to facilitate mathematical verification and we sought to make it plausible that with or without the photoelectric effect electromagnetism has to admit the same model.

But given the mathematics with which it is intended to face the problem the model is a more functional structure for explanation than is logical verification. One model can facilitate the interpretation of certain facts and another can better justify others.

The model adopted by Maxwell is hydrodynamic \( \square \); for him the horizon of physics stops with matter and motion. Therefore, from his viewpoint, the model chosen does not prejudice understanding of the phenomena described. His successors were unable to endorse it because in the first place it forced him to disseminate his treatise with caveats against analogies with the behaviour of fluids, then because he let himself be led into a misunderstanding, believing he could attribute to field variables a *direct dynamic content*.

After him, all attempts to include electrical and magnetic phenomena en bloc among those explainable by mechanics being exhausted, the problem of understanding the relationship between the field variables \( \mathbf{E}(x,y,z,t) \), \( \mathbf{D}(x,y,z,t) \), \( \mathbf{B}(x,y,z,t) \), and \( \mathbf{H}(x,y,z,t) \) and matter and therefore mechanics was posed.

This is a problem of interpretation. It cannot be solved by use of an ad hoc ether. It clearly shows the limit of Maxwell’s model but does not give indications that the mathematical basis is insufficient. Thus H. Lorentz corrects the existing theory \( \square \) by postulating that the kinematic behaviour of electrically charged ponderable bodies gives the *only measurable proof* of the presence of electromagnetic fields. He adjusts the kinematic behaviour of test bodies in the fields by adding to Maxwell’s equations the dynamic law which bears his name. Hereinafter we consider his work with exclusive reference to the problem set here.

According to us, this author’s main purpose was to credit the Maxwell equations no matter how by establishing conventions acceptable to the majority of the scientific community. Just because the burden of proof of the electrical fields is conceived according to gravitation it is not a matter of an explanation of a specific electrical experiment but of the interpretation of mathematical formulas. If it is remembered that retarded potentials are an excellent mathematical artifice it can be concluded that the model proposed as an alternative to hydrodynamics does not seek to be innovative.

If Lorentz set himself the above mentioned purposes the interpretative capacity of his model was distorted. Further analyzing other implications of Lorentz’ model is beyond the scope at hand.

In this paragraph we are not discussing the experimental evidence in favor of the electron but rather the appropriateness of modeling the radiation-matter in-
teraction in electromagnetism with its help. From this point of view the electron hypothesis was judged insufficient at least by all the ‘founding fathers’ of quantum mechanics to account for the experiments. Among these A. Sommerfeld observes that in classical wave theory the electrons are considered in continuous interaction with the ether and that every variation of their movement involves irradiation of waves. After which he says [19], “One imagines an electron in the source point of every spherical wave which generates the electromagnetic field of the spherical wave according to the rhythm of its movement. […] Instead of speaking of an electron we should speak of a solution of Maxwell’s equations which would express the conditions of atom-ether coupling in force upon irradiation”. Although he viewed the interpretation in the framework of a mathematical construction different from Maxwell’s, we believe the color change pointed out is of a more general interest. It means that to have sense physically the electromagnetic fields need not represent substance or energy. They can represent a relationship between objects, for example an electrical coupling. The necessity of representing this relationship by means of a model arises because of the generality and abstractness of the theory.

In effect, the number of material manifestations which we can trace back to electrical phenomenology is not small. In addition to the movement of indices or movable galvanometer elements, to detect electrical phenomena we use sounds, photochemical and electrolytic reactions, and even calorimetry. Tracing back all these manifestations to a single type of abstract mechanical movement does not mean that we have accounted for the mechanism of the manifestations but rather that we intend to adopt a kinetic model for electromagnetism.

We do the contrary of that when we seek to relate all the above mentioned material manifestations to electromagnetism in a unitary manner. As everyone knows Faraday believed electricity to be connatural with the structure of matter. This hypothesis is faithfully reproduced in Maxwell’s equations with the result of offering a theory with a very new conception and different from all the preceding mechanical ones.

Accepting interpretation of the fields as a relation and implementing Maxwell’s equations with a non-mechanical model, electromagnetism appears as a physical theory explaining the body of Faraday’s experiments without attributing any dynamic meaning to the variables. Mathematics describes the electrical and lighting relationship and the explanation of what we have to represent with the relationship depends on the model.

The object of electromagnetism is established by analogy

In the previous paragraph we saw that the electromagnetic theory is difficult to interpret because Maxwell did not allow for anything but electricity and light. But the only experimental manner of acceding to these magnitudes is to transduce them. To clarify, we do not observe light with the eyes but its
manifestation, i.e. luminous or illuminated objects.

As electromagnetism is not a theory of electrical transduction, it would readily be abandoned today if the interpretative problem had not had an experimental solution. The experimental solution is due to Hertz but H. Helmholtz had a primary role therein. The latter author, as usual for his time, felt that all electromagnetism, and not only the single effect, could be verified by analogy with an appropriate mechanism. He decided to draw a parallel with the world of sounds by comparing resemblances and differences at the propagation level.

The acoustic analogy was heuristic in the sense that Einstein wished for his own interpretation of the photoelectric effect. Before Hertz carried out the first of the demonstrative experiments of the propagation of electrical force in the ether, his teacher, Helmholtz, had laid down for acoustics an experimental methodology which has defied time; to evaluate sound fields around acoustic sources he introduced test bodies which he called resonators. As we shall see in paragraph 6 below, Hertz transposed the investigation method exactly as it was from musical acoustics and adapted both field generators and test bodies to the technical requirements of electricity. Since not even Hertz knew anything about antennas, we cannot assert that we would judge his field probes according to present day parameters. We can only observe that Hertz’ so-called dipoles are not the experimental equivalent of the test body prescribed by Lorentz.

We warned that it is possible to doubt the functionality of Lorentz’ electron as a field probe without detriment to the validity of Maxwell’s equations. The experimental confirmation given by Hertz independently of the particular probe (provided it were suitable) used by him can be considered also.

In the paper, über die Beziehungen zwischen Licht und Elektrizität Hertz explains what the experimental confirmation of electromagnetism consists of. “[... between light and electricity there is] a succession of delicate interactions like rotation of the polarization plane with the current, or variation of conduction resistance with light. In these [examples] however there is no direct transduction between light and electricity but the ponderable matter mediates between these two manifestations. We shall not concern ourselves with this group of phenomena [i.e. those of transduction]. There are stricter relationships between light and electricity. I shall defend this statement before you: light is an electrical phenomenon”.

We must not understand identification of light with electricity as an imposition of Hertz on nature. Rather it concerns the solution given by him to the problem of establishing what physical object electromagnetism is concerned with. Today we might say that, with this identification, he inaugurated the radiotelephony era for the purposes of human telecommunications.

The possibility of obtaining and giving information without having to establish direct contact is given naturally and is absolutely not limited to electrical phenomena or to human beings. On the contrary, the possibility of neglecting the peculiarities of the detector or probe for the purposes of electromagnetic telecommunications is postulated by Maxwell and proven experimentally by Hertz.

We mentioned that an effect very similar to Hertz’ photoelectric effect be-
longs to the experimental basis of Maxwell’s equations. Hertz himself, in de-
scribing the fact, considers it marginal in comparison with the verification of
electromagnetism which he has in mind. And yet the photoelectric effect is the
first fact he detected with the experimental arrangement suited to that veri-
fication. According to the theory, the photoelectric effect gives rise to a signal.
Neither the technology for reception thereof nor its decoding nor attribution
thereto of a meaning are prescribed in electromagnetism.

**Inconsistency of Einstein’s heuristic approach with
Millikan’s verification**

If we understand, the energetic interpretation given by Einstein to the photo-
electric effect is heuristic in the sense that he asks if it would not be possible to
formulate a general theory of transformation of light in *something else* in place
of the theory of Maxwellian conception. The theory in the making would be
oriented towards the transduction process and in this case would distinguish the
spark from the negative electricity extracted. At least in this respect the new
theory diverges from the Hertzian basis of telecommunications. But it could be
a theory of electrical phenomena for the same reason. Indeed, even Faraday’s
original experimenting is much richer with facts and leaves a broad margin for
schematization of electrical phenomena beyond theories of light.

Since the theory conceived by Einstein imposes an energy balance of trans-
duction it must postulate the principle of conservation of energy and therefore is
bound to be a linear theory. In accordance therewith the modality hypothesized
for transformation of light in something else must be theoretically represented by
simple processes such as absorption and emission [5]. The tolerance with which
the linearity requirement is transferred to the experiment is not prescribed.

Today a coherent general theory alternative to electromagnetism exits. We
shall not touch here on the question intrinsic to its field of application.

On the other hand the experimental solution given by Millikan does not re-
present for the new theory what the Hertz verification represents for the classical
one. In effect, in the era of this author the theory of electrical circuits was
universally accepted and the photodiode was considered a circuitry component
with full rights. Einstein’s linear equation being reproduced experimentally he
himself observes that he can agree with any linear theory that manages to justify
it.

As mentioned above, metallic surfaces can display the photoelectric effect.
However Einstein does not specify any surface characteristic when he gets the
following heuristic law.

\[ eV = Nh\nu - P \]  \hspace{1cm} (1)

in the very broad context of light production and transformation energetics.
In the formula, \( e \) is the charge per gram-equivalent weight of monovalent ions, \( V \)
is the potential to which the surface of the irradiated solid body is brought, \( N \) is the number of real molecules thereof, \( P \) is the potential with which electricity is held therein and is termed work function, and \( h\nu \) is the quantized light energy corresponding to incident radiation with frequency \( \nu \).

It seems to us that in the Einstein formulation two misunderstandings are introduced.

1. Faraday’s electrolytic ions, for each reagent, met the specified chemical composition to the electrolytic purity grade. Today we can obtain them chemically more or less pure than this and verify their properties. The degree of purity of the electron on the other hand has always been associated with metallic conduction.

2. If, as we are led to think, in 1905 Einstein was not predicting L.A.S.E.R., he attributes to natural light model characteristics taken entirely from Maxwell’s theory. Today, on the contrary, one should decide either that L.A.S.E.R. is not a black radiator or to which black bodies Planck’s theory applies.

If the experimenter does not cautiously appraise the challenge placed on measurement he will have the alternative of an interpretation in agreement with electromagnetism also or a mistaken one. Obviously to discuss transformation or transduction of light in something else it is necessary to attack experimentally the question upstream of the place where the photoelectric effect pertains to an electromagnetic radiation and to a metallic electric current. Since concomitantly with electromagnetism it is established that electric phenomena can be referred objectively (i.e. measured) the upstream place where the question should be faced is the one in which the electrical effects are separated from their material manifestations.

We found no evidence that Millikan had tried to distinguish the so-called work function \( P \) from the Volta effect. He merely subtrabs the second value in volts from the first. But the justification of the validity of the Einstein equation not only ignores transduction at the measurement level but even neglects to include in the energy balance concomitant chemical transformations which have nothing to do with the measurement procedure chosen. The most considerable of these transformations is the formation of a patina on the cathode but it is not the only one.

If he were to reduce the non electrical side effects by lowering the radiant power and/or using less inflammable cathodes and/or improving the vacuum in the cathode ray tube, he would verify Einstein’s heuristic equation under the hypothesis of Maxwell’s theory (i.e. regardless of the reception modality).

But Millikan might have reached the conclusion that, under the measurement conditions in which none of the ‘excess’ side effects were still perceptible, neither would he have been able to confirm Einstein’s equation numerically beyond all doubt. Thus he undoubtedly verified it but in the framework of what general theory?
The photoelectric effect mechanism

Up to this point we have sought to say that the Maxwell-Hertz theory explicitly disregards the characteristics of transduction and in addition that even the theory proposed by Einstein, although it intends to appraise the transduction energy balance, must disregard the specification of a particular mechanism.

We are now proposing a mechanism which accounts for the photoelectric effect and saying that it is the one presently suggested in electromagnetism.

We shall proceed as follows. First we shall review Helmholtz’ mechanical analogy, then we shall explain which function has the photoelectric effect in Hertz’ experiment. Lastly we shall transfer to the UV excitation the same receiving and transmission modality observed for Hertzian waves. This is possible under the Maxwellian radiation hypotheses.

Helmholtz’ intellectual contribution to Hertz

Many mechanical systems can be made to vibrate under appropriate conditions. Oscillations are determined of such an entity as to endanger the integrity of the structure only in a few.

For example, if the wheels of the vehicle are not balanced, at certain speeds the steering wheel vibrates in an annoying manner around its axis. On the contrary, if they are balanced this does not occur at normal speeds. In an analogous manner a ship cannot exceed a certain cruising speed without the planking beginning to tremble. In addition to the creaking, the sailing ship’s structure, differently from the vehicle, emits in creaking a sound similar to a note. In navigation it is believed that the wave represents a sufficient stress and other singing effects are not sought. In the construction of musical instruments, on the contrary, the aim is to obtain some effect of this kind from the soundbox while the vibration is sustained.

A hammer blow given to a shroud stretched between two steel girders, even if it is perceptible, does not correspond to a musical sound. In addition, without a soundbox there is no intensity of force capable of stressing the rope in such a manner as to give rise to a musical sound. So apparently the function of the soundbox is to give sonority to the movement of a plucked, rubbed or struck tight chord.

Going a bit further, we can attribute to this the property of amplifying the vibration of the chord, possibly with distortion. Now the amplification consists of pulling the mass of contained air and the immediately surrounding mass in some movement. We can imagine that the soundbox has the faculty of adapting the movement of the chord to that of the air.

This experimental base does not allow enunciation of a physical law putting the vibration frequency of the chord in correspondence with the perceived note.

In the meantime if the chord is represented 'with distributed mass' it is a simple pendulum only in a first approximation.

But let us hypothesize that the chord vibrations are stationary and the isochronism is controlled stroboscopically. Secondly the soundbox necessary
for perception of the sound does not develop pendular motion. If we except organ pipes it doesn’t have even by far a one-dimension structure.

In the third place the air filling the space behaves in general as an even worse oscillator.

We might even hazard the hypothesis that the air does not at all enter into oscillation during the sound. In particular, it seems to us illusory to think that smoke or fog or a flame would help demonstrating the movement more instantly or faithfully than does the soundbox.

Instead it is certain that the air behaves as a channel of transmission in relation to sound and consequently the individual without hearing defects perceives sounds and noises. We can agree to call both of them ‘signals’ as long as the movement of the air itself does not become perceptible, which is what takes place for example during explosions. The signals are transduced into sounds by the ear. Under loose conditions we can ignore transduction. But a theory independent of the modality of transduction is a signal theory. Only in this kind of theory is it unimportant to call signals ‘sounds’ or ‘noises’. Obviously Helmholtz implicitly makes this assumption.

Now let us summarize the work of Helmholtz in relation to the experiment of Hertz. He considers the siren as an instrument capable of sustaining a certain note as long as desired. He associates with the pitch of tones perceived in the air the linear speed of rotation of the siren disk holes which produce them. These speeds are constant in modulus. It is understood at this stage that the frequency of rotation which equals the pitch of the tone supplies an objective measurement after disregarding the attacking and releasing transients. But it is the mere instrumental recording of a fact which, if we are musicians, we are capable of evaluating independently and equally objectively by ear. In a subsequent stage, making use of the instrument, we can ‘educate’ the ear to hearing without being musicians.

In effect, having chosen 440Hz for the reference frequency attributed to the tuning fork, Helmholtz is able to reduce the musical chords to simple frequency relationships. In this manner it is seen that the quality of sound of the soundboxes as obtained by spectral analysis in accordance with Fourier is not simple and that the consonance or dissonance of a chord concerns the musical tone more than the pitch of a single partial tone, commonly the prime tone.

Studying the phenomenon better it is seen that as loudness increases, non-linear effects can occur. The non-linearity consists of the fact that we hear tones which the instrument did not produce. These tones which Helmholtz calls combinatorial tones are sums and differences of the tones emitted provided they are perceptible.

The linear case of these effects is perceived as beats. During the beats, sounds of similar pitch emitted by different instruments interfere temporally. Today beats can be used for tuning; the slower they are the more similar is the pitch of the sound of the two instruments compared.

It should be said that -

1. Helmholtz evaluates the spectral sound distribution in the space around the siren by measuring with tuned sensors invented by himself the intensity of
several persistent simple tones. Therefore he seems to locate the sounds in the room.

2. Even though he calls these sensors ‘resonators’ they cannot be excited until they oscillate freely when the external stress is broken. They cannot be thought of as sound sources. Therefore, in the same manner as the ear or other soundboxes, they amplify selectively by coupling with the air.

**Acoustic analogy due to the Hertz photoelectric effect**

Hertz possessed a battery-powered RCL secondary electrical circuit which he used as a transmitter and also an RCL with receiver function. For the purpose of emphasizing the photoelectric effect he fed the receiver in series with the same battery as the transmitter. A mercury switch was part of the primary circuit.

Hertz didn’t feed the transmitter persistently during the experiment nor did he use the charge transient but the discharge transient. Upon opening the switch, a spark went off at the spark gap between the transmitter capacitor plates, two small polished, perfectly clean metal balls. Simultaneously the spark went off at the receiving RCL spark gap provided the latter was less than approximately 3 meters away. The two spark gaps also had to be facing each other and any object placed between them could prevent the spark to the receiver from going off, provided it completely hid a band beyond extreme violet. Hertz determined the frequency of this band by dispersion through a quartz prism. He named this phenomenon the photoelectric effect.

A good quality factor Q was an essential requisite on the receiver. If the transmitter also had a good Q, a mutual reinforcement of the spark could be noted.

Let us consider the interpretation. Hertz thought that his secondary circuits were equipollent with soundboxes. But the acoustic box serves to both selectively amplify and broadcast music. On the contrary, modern broadcasting makes use of antennas distinct from oscillating circuits.

If in addition to tuning resonators in frequency with each other Hertz had adapted both to the transmission channel, he could have avoided consuming the power necessary to produce sparks and would have received a less noisy signal. In reality he needed to receive and transmit sparks because he had no lower frequency reception techniques available.

From the point of view of reception the spark transduces an electric signal and represents it so to speak. The spark produced by an electrical circuit on the other hand is not analogous to a simple tone nor to a musical sound. It can be said that having neglected the last consideration was fatal to the Hertzian interpretation. We shall attempt to repropose it while allowing for it.

Hertz precisely ‘is not concerned’ with adapting the impedance. This is equivalent of believing a priori the inductive coupling to be weak or even believing it to be of the order of magnitude of the acoustic one.

If the assumption were true the Hertzian radiofrequency (r.f.) receiver would function as a wavemeter, recording amplitude maxima or, more correctly, intensity maxima of a continuous wave (CW) emitted at the resonance frequency.
A wavemeter is Helmholtz' resonator. When it is placed in the trough of a stationary wave, i.e. in a zone where interference does not produce cancellation, it amplifies a persistent sound, possibly introducing distortions. By analogy, Hertz prefigures to himself receiving a sequence of sparks timed at radiofrequency as long as wanted. In truth, Hertz' transmitter does not broadcast a continuous wave but a free induction decay (FID). Hertz nevertheless prefigures to himself that the r.f. FID of a transmitting resonator gives rise to a goodly number of discharge sparks when fed at the highest power. On the other hand he observes a single spark from the spark gap of the transmitter and, at the same time, the reception signal (a spark). So he concludes that the electric emission is really oscillating at radiofrequency but even more damped than that of a common diapason.

The assumption is reasonable and the consequences plausible. Its falsification depends on the existence in trade of klystrons. In comparison with klystrons, any mechanical vibration is damped, even that of the diapason, despite the fact that it is the only musical instrument able to transmit a FID and which transmits it on condition it be adapted correctly to the air.

If Hertz had considered this point and had adapted the impedance in addition to tuning the receiver to the transmitter, he would have noticed that not only the transmitter but the receiver also radiates when excited. In addition, under coupling conditions phase relationships are determined.

The symmetry of behaviour between electrical transmitter and receiver can be such as to make them indistinguishable as regards function. On the contrary, only diapasons at the same nominal frequency can be acoustically coupled during transients and in this case the beat phenomenon is recorded.

By analogy Hertz would have received a voltage or current signal corresponding to the envelope of interference working at low power and low frequency (amplitude demodulation). Since this procedure does not give rise to a spark he would have had to develop the reception circuit further.

The need to detect sparks arises from the absence of this circuit. So Hertz adjusts the transmitting circuit so that the overvoltage at the spark gap would produce them. According to Faraday the excess current corresponds to the extra current of opening of the switch but the sudden trigger of the light discharge depends on disconnection of the mercury from the circuit. The analogy given to the diapason would be a hammer blow which produces a clang even in the disadapted diapason. According to Helmholtz, to this clang must be attributed an origin different from the note a' due to the fact that it is emitted isotropically and is audible. According to him these are frequency combination tones typical of the metallic structure.

The mechanism identified by Helmholtz explains the emission of the spark by an electrical circuit by analogy. The resonance coupling in the UV on the other hand is explained the same way electrical oscillations of coupled circuits are explained, when the behaviour of linear electrical circuits is the model of electromagnetism. This allows the statement that the photoelectric effect is an inductive coupling in the UV. It is very selective, hence strong and in addition the requisites of adaptation for transmission in vacuum are met. This interpre-
tation would not be possible if Hertz had made use of a coherer or a photodiode for reception of the spark.

Conclusion

It seems to us that Einstein’s proposal to develop formal structures capable of giving a simple description of the basic phenomena hasn’t lost its appeal. It even seems to us that the photoelectric effect could be fairly considered a typical and fundamental phenomenon. It should not be surprising that in its experimental characterization according to Hertz it appears basic for electromagnetism.

Its interpretation is not elementary because it is given in the framework of a model which assumes simple behaviour of electrical circuits. In this case, indeed, its observation is associated with the non-linear behaviour of circuits.

We have showed that the photoelectric effect can be interpreted with the help of the analogy with sounds, and that it can be explained in the framework of Maxwell theory.

We believe however that the explanation of the photoelectric effect might be simplified starting from a different model of Maxwell-Hertz electromagnetism.

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