Modern Physics

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The Photoelectric Effect

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Hertz Finds Maxwell's Waves: and Something Else

The most dramatic prediction of Maxwell's theory of electromagnetism, published in 1865, was the existence of electromagnetic waves moving at the speed of light, and the conclusion that light itself was just such a wave. This challenged experimentalists to generate and detect electromagnetic radiation using some form of electrical apparatus. The first clearly successful attempt was by Heinrich Hertz in 1886. He used a high voltage induction coil to cause a spark discharge between two pieces of brass, to quote him, "_Imagine a cylindrical brass body, 3 cm in diameter and 26 cm long, interrupted midway along its length by a spark gap whose poles on either side are formed by spheres of 2 cm radius._" The idea was that once a spark formed a conducting path between the two brass conductors, charge would rapidly oscillate back and forth, emitting electromagnetic radiation of a wavelength similar to the size of the conductors themselves.

To prove there really was radiation emitted, it had to be detected. Hertz used a piece of copper wire 1 mm thick bent into a circle of diameter 7.5 cms, with a small brass sphere on one end, and the other end of the wire was pointed, with the point near the sphere. He added a screw mechanism so that the point could be moved very close to the sphere in a controlled fashion. This "receiver" was designed so that current oscillating back and forth in the wire would have a natural period close to that of the "transmitter" described above. The presence of oscillating charge in the receiver would be signaled by a spark across the (tiny) gap between the point and the sphere (typically, this gap was hundredths of a millimeter). (It was suggested to Hertz that this spark gap could be replaced as a detector by a suitably prepared frog's leg, but that apparently didn't work.)

The experiment was very successful - Hertz was able to detect the radiation up to fifty feet away, and in a series of ingenious experiments established that the radiation was reflected and refracted as expected, and that it was polarized. The main problem - the limiting factor in detection -- was being able to _see_ the tiny spark in the receiver. In trying to improve the spark's visibility, he came upon something very mysterious. To quote from Hertz again (he called the transmitter spark _A_, the receiver _B_): "_I occasionally enclosed the spark B in a dark case so as to more easily make the_

observations; and in so doing I observed that the maximum spark-length became decidedly smaller in the case than it was before. On removing in succession the various parts of the case, it was seen that the only portion of it which exercised this prejudicial effect was that which screened the spark B from the spark A. The partition on that side exhibited this effect, not only when it was in the immediate neighbourhood of the spark B, but also when it was interposed at greater distances from B between A and B. A phenomenon so remarkable called for closer investigation."

Hertz then embarked on a very thorough investigation. He found that the small receiver spark was more vigorous if it was exposed to ultraviolet light from the transmitter spark. It took a long time to figure this out - he first checked for some kind of electromagnetic effect, but found a sheet of glass effectively shielded the spark. He then found a slab of quartz did not shield the spark, whereupon he used a quartz prism to break up the light from the big spark into its components, and discovered that the wavelength which made the little spark more powerful was beyond the visible, in the ultraviolet.

In 1887, Hertz concluded what must have been months of investigation: "… *I confine myself at present to communicating the results obtained, without attempting any theory respecting the manner in which the observed phenomena are brought about.*"

Hallwachs' Simpler Approach

The next year, 1888, another German physicist, Wilhelm Hallwachs, in Dresden, wrote:

"*In a recent publication Hertz has described investigations on the dependence of the maximum length of an induction spark on the radiation received by it from another induction spark. He proved that the phenomenon observed is an action of the ultraviolet light. No further light on the nature of the phenomenon could be obtained, because of the complicated conditions of the research in which it appeared. I have endeavored to obtain related phenomena which would occur under simpler conditions, in order to make the explanation of the phenomena easier. Success was obtained by investigating the action of the electric light on electrically charged bodies.*"

He then describes his very simple experiment: a clean circular plate of zinc was mounted on an insulating stand and attached by a wire to a gold leaf electroscope, which was then charged negatively. The electroscope lost its charge very slowly. However, if the zinc plate was exposed to ultraviolet light from an arc lamp, or from burning magnesium, charge leaked away quickly. If the plate was positively charged, there was no fast charge leakage. (We showed this as a lecture demo, using a UV lamp as source.)

Questions for the reader: Could it be that the ultraviolet light somehow spoiled the insulating properties of the stand the zinc plate was on? Could it be that electric or magnetic effects from the large current in the arc lamp somehow caused the charge leakage?

Although Hallwach's experiment certainly clarified the situation, he did not offer any theory of what was going on.

J.J. Thomson Identifies the Particles

In fact, the situation remained unclear until 1899, when Thomson established that the ultraviolet light caused *electrons* to be emitted, the same particles found in cathode rays. His method was to enclose the metallic surface to be exposed to radiation in a vacuum tube, in other words to make it the cathode in a cathode ray tube. The new feature was that electrons were to be ejected from the cathode by the radiation, rather than by the strong electric field used previously.

By this time, there was a plausible picture of what was going on. Atoms in the cathode contained electrons, which were shaken and caused to vibrate by the oscillating electric field of the incident radiation. Eventually some of them would be shaken loose, and would be ejected from the cathode. It is worthwhile considering carefully how the *number* and *speed* of electrons emitted would be expected to vary with the *intensity* and *color* of the incident radiation. Increasing the intensity of radiation would shake the electrons more violently, so one would expect more to be emitted, and they would shoot out at greater speed, on average. Increasing the frequency of the radiation would shake the electrons faster, so might cause the electrons to come out faster. For very dim light, it would take some time for an electron to work up to a sufficient amplitude of vibration to shake loose.

Lenard Finds Some Surprises

In 1902, Lenard studied how the energy of the emitted photoelectrons varied with the intensity of the light. He used a carbon arc light, and could increase the intensity a thousand-fold. The ejected electrons hit another metal plate, the collector, which was connected to the cathode by a wire with a sensitive ammeter, to measure the current produced by the illumination. To measure the energy of the ejected electrons, Lenard charged the collector plate negatively, to repel the electrons coming towards it. Thus, only electrons ejected with enough kinetic energy to get up this potential hill would contribute to the current. Lenard discovered that there was a well defined minimum voltage that stopped any electrons getting through, we'll call it V_{stop}. To his surprise, he found that V_{stop} did not depend at all on the intensity of the light! Doubling the light intensity doubled the *number* of electrons emitted, but did not affect the *energies* of the emitted electrons. The more powerful oscillating field ejected more electrons, but the maximum individual energy of the ejected electrons was the same as for the weaker field.

But Lenard did something else. With his very powerful arc lamp, there was sufficient intensity to separate out the colors and check the photoelectric effect using light of different colors. He found that the maximum energy of the ejected electrons *did* depend on the color --- the shorter wavelength, higher frequency light caused electrons to be ejected with more energy. This was, however, a fairly qualitative conclusion --- the energy measurements

were not very reproducible, because they were extremely sensitive to the
condition of the surface, in particular its state of partial oxidation. In the best
vacua available at that time, significant oxidation of a fresh surface took
place in tens of minutes. (The details of the surface are crucial because the
fastest electrons emitted are those from right at the surface, and their binding
to the solid depends strongly on the nature of the surface --- is it pure metal
or a mixture of metal and oxygen atoms?)
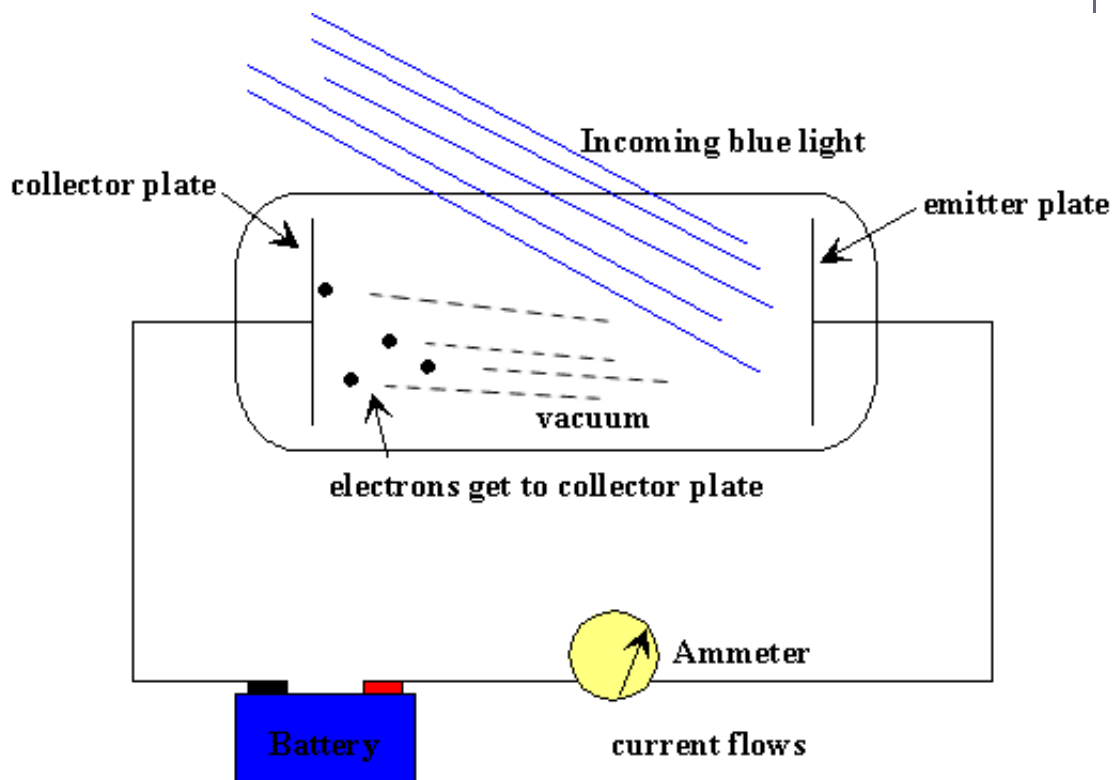
Question: In the above figure, the battery represents the potential Lenard
used to charge the collector plate negatively, which would actually be a
variable voltage source. Since the electrons ejected by the blue light are
getting to the collector plate, evidently the potential supplied by the battery is
less than V_{stop} for blue light. Show with an arrow on the wire the direction of
the electric current in the wire.

collector plate

Incoming red light

electrons don't get to plate

Ammeter

Battery

no current flows
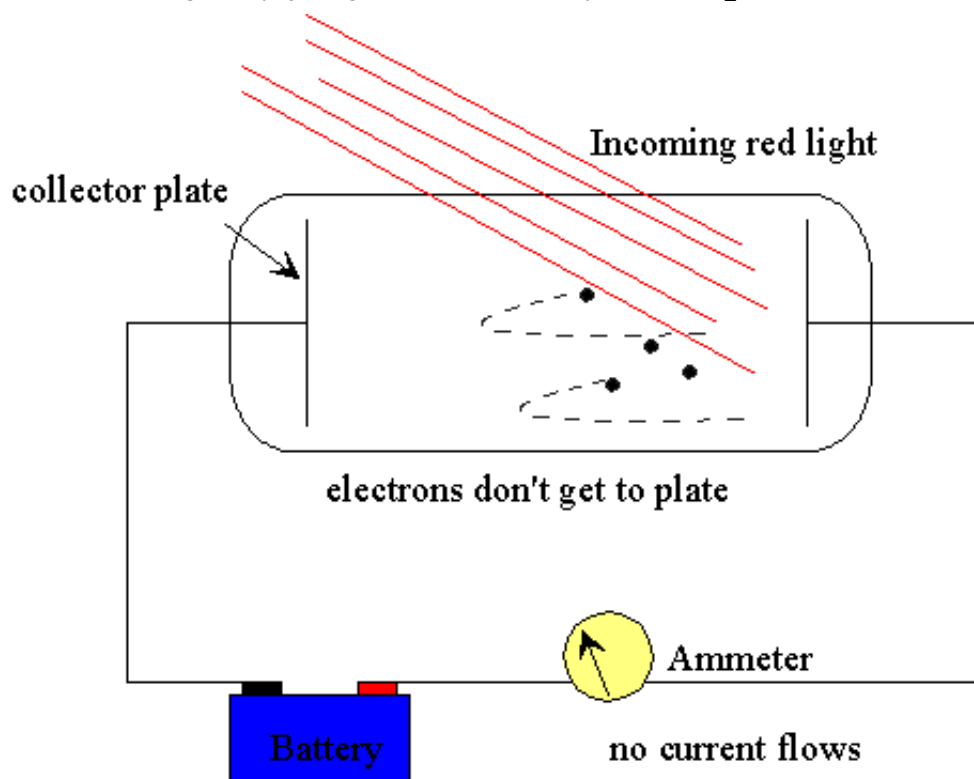
Einstein Suggests an Explanation

In 1905 Einstein gave a very simple interpretation of Lenard's results. He just assumed that the incoming radiation should be thought of as quanta of frequency hf, with f the frequency. In photoemission, one such quantum is absorbed by one electron. If the electron is some distance into the material of the cathode, some energy will be lost as it moves towards the surface. There will always be some electrostatic cost as the electron leaves the surface, this is usually called the work function, W. The most energetic electrons emitted will be those very close to the surface, and they will leave the cathode with kinetic energy

$$E = hf - W.$$

On cranking up the negative voltage on the collector plate until the current just stops, that is, to V_{stop}, the highest kinetic energy electrons must have had energy eV_{stop} on leaving the cathode. Thus,

$$eV_{stop} = hf - W$$

Thus Einstein's theory makes a very definite quantitative prediction: if the frequency of the incident light is varied, and V_{stop} plotted as a function of frequency, the slope of the line should be h/e.

It is also clear that there is a minimum light frequency for a given metal, that for which the quantum of energy is equal to the work function. Light below that frequency , no matter how bright, will not cause photoemission.

Millikan's Attempts to Disprove Einstein's Theory

If we accept Einstein's theory, then, this is a completely different way to measure Planck's constant. The American experimental physicist Robert Millikan, who did not accept Einstein's theory, which he saw as an attack on the wave theory of light, worked for ten years, until 1916, on the photoelectric effect. He even devised techniques for scraping clean the metal surfaces inside the vacuum tube. For all his efforts he found disappointing results: he confirmed Einstein's theory, measuring Planck's constant to within 0.5% by this method. One consolation was that he did get a Nobel prize for this series of experiments.

References

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The Project Physics Course, Text, Holt, Rinehart, Winston, 1970

Life of Lenard

Life of Millikan