The Photoelectric Effect

I. Introduction
The photoelectric effect was discovered by Heinrich Hertz in the 1880’s when he observed that under the right conditions, when light is shined on a metal, electrons are ejected from the surface of the metal. This process was called photoemission. In 1880 light was believed to be completely wavelike in nature and fully described by James Clerk Maxwell's new theory of electromagnetism—the famous "Maxwell Equations”—which clearly demonstrated that light was a wave. Although the wave model and the classical theory of electricity and magnetism were able to explain most known properties of light, they could not explain some subsequent experiments. The most striking of these is the photoelectric effect, also discovered by Hertz: when light strikes a metal surface, electrons are sometimes ejected from the surface. As one example of the difficulties that arose, experiments showed that the kinetic energy of an ejected electron is independent of the light intensity. This finding contradicted the wave theory, which held that a more intense beam of light should add more energy to the electron. Light must be regarded as having a dual nature: Light exhibits the characteristics of a wave in some situations and the characteristics of a particle in other situations. Light is light, to be sure. However, the question “Is light a wave or a particle?” is inappropriate. Sometimes light acts like a wave, and at other times it acts like a particle. Some aspects of the photoelectric effect seemed impossible to reconcile with this wave view of light. For example, the emission of particles from a surface in response to incident light depended on the frequency of the light, rather than the intensity. According to the classical theory, incident light should be steadily absorbed by the surface of the metal until enough energy had been absorbed to eject a particle. Hertz found that this was not true; in fact, for some frequencies of light, no amount of radiation was sufficient to eject a particle while for other frequencies any amount was sufficient. The photoelectric effect, along with the “ultraviolet catastrophe” discovered in the study of blackbody radiation and Compton scattering eventually toppled the great classical theory of electromagnetism and shook the foundations of classical physics. However, light is not only a wave but also it is particulate—and it travels in little energy bundles called photons. The energy of one of these photons is $hf$, where $h$ is the fundamental constant of nature proposed by Max Planck to explain blackbody radiation, and $f$ is the frequency of the photon.

The photoelectric effect together with the problem of blackbody radiation were the two experimental foundations on which the theory of quantum physics was constructed. For this reason the photoelectric effect can be considered one of the most important experiments in the history of physics. From an experimental point of view the photoelectric effect is also significant because it can provide a numerical value for Planck's constant.

Light falling on a metal can cause electrons to be ejected from the metal. This is known as the **photoelectric effect**.
The figure below shows a circuit that can be used to analyse the photoelectric effect.

Expanding on Planck's quantum idea, the energy in the light is not spread uniformly throughout the beam of light. Rather, the energy of the light is contained in "packets" or quanta (the plural of quantum, a single "packet") each with energy of

\[ E = h f \]

where again \( h \) is Planck's constant and \( f \) is the frequency of the light. All of the energy in one quantum -- now called a photon -- is given to one electron. For light with a low frequency, the energy, \( E = h f \), in one quantum of light would not be great enough to release an electron. For light with a higher frequency, a frequency greater than some particular threshold frequency, there would be enough energy and the electron would be ejected. From the conservation of energy, we would expect the electron to leave with kinetic energy \( KE \) given by

\[ h f = KE + W \]

\[ KE = h f - W \]

where \( W \) is the amount of work that must be done to separate an electron from the metal. For the least strongly bound electrons (the ones easiest to tear away from the metal) this amount of work is known as the "work function" and is labelled \( W_0 \). These electrons will leave with the greatest kinetic energy \( KE_{\text{max}} \) which is given by

\[ h f = KE_{\text{max}} + W_0 \]

\[ KE_{\text{max}} = h f - W_0 \]
An increase in the intensity of the light means an increase in the number of photons (or "packets" or quanta of energy) so more electrons will be ejected. But each electron will have originated from a photon of the same energy so there will be no increase in the maximum energy of the electrons.

An increase in the frequency of the light will cause an increase in the maximum kinetic energy of the electrons according to our equation above,

\[ KE_{\text{max}} = h f - W_o \]

Kinetic Energy can never be negative so this equation defines a threshold frequency, \( f_o \), from

\[ hf_o = W_o \]

If the frequency of the light is below this threshold frequency \( f_o \), there will be no photoelectrons ejected from the metal.

The predictions of Classical Physics, using just the electromagnetic wave nature of light, are drastically different. In 1913 and 1914 Robert A Millikan (famous for measuring the charge on an electron with his "oil drop experiment") carried out careful experiments and measured precisely what the above theory predicted.

If a beam of light is pointed at the negative end of a pair of charged plates, a current flow is measured. A current is simply a flow of electrons in a metal, such as a wire. Thus, the beam of light must be liberating electrons from one metal plate, which are attracted to the other plate by electrostatic forces. This results in a current flow.
In classical physics, one would expect the current flow to be proportional to the strength of the beam of light (more light = more electrons liberated = more current). However, the observed phenomenon was that the current flow was constant with light strength, yet varied strongly with the wavelength of light such that there was a sharp cut-off and no current flow for long wavelengths.

Each photon carries a specific energy related to its wavelength, such that photons of short wavelength (blue light) carry more energy than long wavelength (red light) photons. To release an electron from a metal plate required a minimal energy that could only be transferred by a photon of energy equal or greater than that minimal threshold energy (i.e. the wavelength of the light had to be a sufficiently short). Each photon of blue light released an electron. But all red photons were too weak. The result is no matter how much red light was shown on the metal plate, there was no current.
**Uses.**

Photoelectric cell or photocell is a device whose electrical characteristics (e.g., current, voltage, or resistance) vary when light is incident upon it. The most common type consists of two electrodes separated by a light-sensitive semiconductor material. A battery or other voltage source connected to the electrodes sets up a current even in the absence of light; when light strikes the semiconductor section of the photocell, the current in the circuit increases by an amount proportional to the intensity of the light.

The photovoltaic type of photoelectric cell, when exposed to light, can generate and support an electric current without being attached to any external voltage source. Such a cell usually consists of a semiconductor crystal with two zones composed of dissimilar materials. When light shines on the crystal, a voltage is set up across the junction between the two zones. A phototransistor, which is a type of photovoltaic cell, can generate a small current that acts like counters, automatic door openers, and intrusion alarms. Photocells in such devices are popularly known as electric eyes.

**Practical results**

In an experiment performed in 1915 (and published in *Physical Review*, vol VII, p. 362 (1916)), Robert Andrews Millikan set up a system in which he could measure the photoelectric effect accurately from freshly scraped surfaces of alkali metals. The glass vessel shown below was evacuated; one of the metal samples mounted on the wheel W at the centre was rotated to bring it next to the knife K, which scraped it clean; then the sample was rotated 180 degrees to face light shining through aperture O.
Millikan's data is shown below. He shone light of various frequencies (plotted on the horizontal axis; note the factor of 10 to the 13’th power!) on the metal plate, and determined the minimum voltage (plotted on the vertical axis) necessary to halt the induced current.

- Does the stopping voltage increase linearly with frequency of the incident light?
- What is the value of Planck's constant $h$ based on this data?
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