The Photoelectric Effect

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1 The Recent History of Light

Light is constantly interacting with the universe and the question of ”what actually is light?” has been the bright center of scientists’ discourses throughout history. Over the course of scientific history, the understanding of what light is and how it interacts with the universe has changed, and most interestingly, these fluctuations in understanding occurred in our relatively recent past. The observed phenomenon which lead scientists to their current understanding that light acts as a wave and is defined in chunks, is known as the photoelectric effect.

Light has been the pinnacle of debate throughout the course of scientific history. In the early eighteenth century, the argument about the nature of light divided the science community. One group of scientists, who advocated the wave theory, centered their arguments on the discoveries of Dutchman Christian Huygens. Huygens’ principle is the theory that every point a luminous disturbance meets turns into a source of the spherical wave itself. The sum of the secondary waves, which are the result of the disturbance, determines what form the new wave will take [SD16].This theory advocates that each light wave has a wave front which is made up of infinitely many spherical waves oscillating. These wave fronts then were explained to have an energy associated with the intensity of the light. The other camp cited Sir Isaac Newton’s prism experiments as proof that light must be made of particles. Newton’s observations displayed light proceeding in a straight line until it was refracted, absorbed, reflected, diffracted or disturbed in some other way.

The scientific community accepted the wave model of light after Thomas Young applied Huygens’ principle to his slit experiment in the early 19th century. In his experiment, Young demonstrated the wavelike characteristics of light by shining a beam at a screen with only two slits cut in it. He placed another screen some distance behind this slit screen in order to observe the behavior of light as it passes through. Young took note of a multiple slit pattern that appeared on the viewing screen which demonstrated more than two distinguishable lines of light. These multiple slits were hypothesized to be the overlap of the diffracted light waves and was denoted as the term *constructive interference*. He concluded that light must be a wave in order to constructively display multiple slits on the viewing screen [SD16].

By the middle of the 19th century, scientists were becoming increasingly convinced of the wave-like character of light. The final blow to the particle theory, was when the English physicist James Clerk Maxwell discovered that all forms of electromagnetic radiation represent a continuous spectrum, and travel through a vacuum at the same speed: $2.997\,924\,58 \times 10^{8}\,\mathrm{m/s}$ [SD16]. It seemed as though the basic questions of light and optical theory had finally been answered. However, later in the 19th century, scientists discovered a phenomenon denoted as the photoelectric effect by German physicist Philipp Lenard. The photoelectric effect changed the way scientists understood electromagnetic radiation and ignited the engineering of ground breaking technologies as well as the ideas which now make up present day quantum physics.

2 The Photoelectric Effect

The photoelectric effect occurs when electrons are emitted from an illuminated surface. In experiments demonstrating the photoelectric effect, light is shined at a metal surface from which electrons start to be emitted from. The entire interaction between the light and the metal surface is held inside a vacuum so that the electrons don’t have a chance to interact with air. There are properties that can be measured from this interaction. One property is the rate of emitted electrons, or *photoelectrons*, measured as an electric current. This measurement is achievable by having a collector acting as a top plate of a capacitor connecting to a circuit which receives the freshly emitted photoelectrons. If an ammeter is embedded in the circuit in series, the electric current is easily measurable. Another measurable property is the maximum kinetic energy of the electrons; this can be measured by applying a negative potential to the collector. Setting this negative potential at a certain value will repel the higher energy electrons. This leaves only a certain amount of electrons able to climb the potential energy hill. If the potential difference between the emitting surface and the collector is ΔV, then electrons, with charge q, travelling from the emitting surface to the collector would gain a potential energy of $\Delta U = q\Delta V$. This potential energy could also be measured by connecting a voltmeter in parallel to the circuit [Kra19]. See figure 1 to understand the circuit schematic.

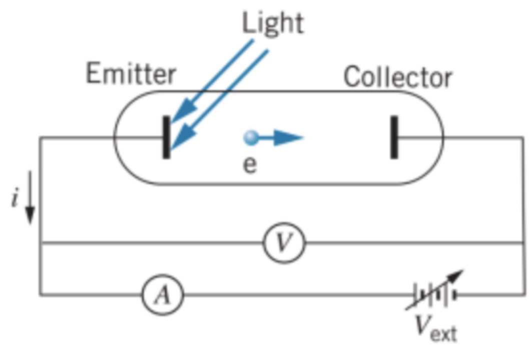

Figure 1: Here is a diagram of an apparatus for observing the photoelectric effect. The flow of electrons is denoted i, the ammeter as A, a variable voltage source V_ext which establishes a potential difference between the emitter and the collector. This is measured by the voltmeter V.

As the magnitude of the potential difference is increased, there will be a point when even the most energetic electrons will not have enough kinetic energy to reach the collector. This potential is called the *stopping voltage* V_s. The stopping voltage is determined by increasing magnitude of the voltage until the current displayed on the ammeter drops to 0. At this point, the maximum kinetic energy of the electrons as they leave the emitting surface is equal to the kinetic energy lost by the electrons that climbed the electric potential hill [Kra19].

2.1 Classical Interpretation

The classical wave theory of the photoelectric effect predicts a handful of things about the properties of photoelectrons. One prediction is that the maximum kinetic energy of the electrons should be proportional to the intensity of the radiation. In the classical wave theory a wave is represented with its own oscillating electric field as well as magnetic field. Classical intensity has the following relationship with electric field amplitude of a light wave: $I = \frac{1}{2\mu_0 c}E_0^2$ where μ_0 is the permeability of free space, c is the speed of light, and E_0 is the electric field amplitude of a classical light wave [Kra19]. As the intensity of the light increases then the electric field amplitude of the wave increases, meaning stronger electric forces, inducing stronger accelerations on the illuminated surface. Overall, the idea here is as the brightness of the light source increases, more energy is delivered to the surface, the electric field is therefore greater in strength, and the electrons should have greater kinetic energy thus greater stopping voltage. See figure 2.

The second prediction is that the photoelectric effect should occur for light of any frequency or wavelength. According to the wave theory, the effect the electromagnetic wave has on the surface is purely correlated with energy. So as long as the light is intense enough to release electrons, the photoelectric effect should occur no matter the frequency or wavelength. See figure 3.

The third prediction entails that the first electrons should be emitted in a time interval of the order of seconds after the radiation begins to strike the surface. In the wave theory, the energy of the wave is uniformly distributed over the wave front [Kra19]. If the electron absorbs energy directly from the wave, the amount of energy delivered to any electron is determined by how much radiant energy is incident on the surface area in which the electron is confined. Assuming this area is about the size of an atom, a rough calculation leads to an estimate that the time lag between turning on the light source and observing the first photoelectrons should be on the order of seconds. This rough time interval calculation involves the intensity I, the area which is illuminated A,and the work function of the material ϕ. The time interval Δt which estimates the time it takes for the first photoelectron to be emitted is expressed as $\Delta t = \frac{\phi}{IA}$.

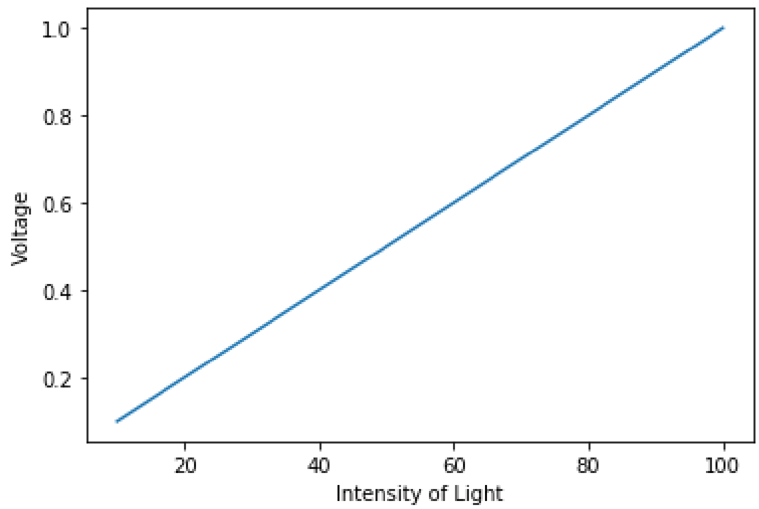

Figure 2: Plot of the classical prediction of the relationship between Intensity of light source and the voltage.

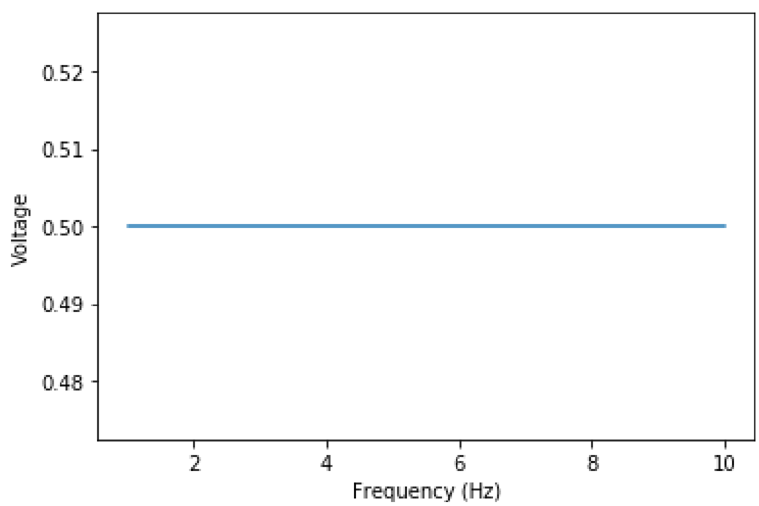

Figure 3: Plot of the classical prediction of the relationship between frequency of light source and the voltage.

2.2 Observed Results

It turns out the observed results are completely inconsistent with all of the classical predictions. By the year 1902 the experimental characteristics were well known. The first observation was that for a fixed value of the wavelength or frequency of the light source, the maximum kinetic energy of the emitted photoelectrons (determined by the stopping voltage) is totally independent of the intensity of the light source [Kra19]. Figure 4 displays data of the stopping voltage at different intensities of light from a recently conducted photoelectric effect experiment at Carthage College by undergraduate physicists. Due to uncertainties in measurements, there is a slight trend upwards captured by the fit result, however the difference in percentage of light intensity does not have as much an impact as predicted by the classical theory. The stopping voltage does not deviate significantly when the light source has a higher intensity.

The second observed characteristic of the photoelectric effect is that the frequency of the light is directly proportional to the kinetic energy of the emitted photoelectrons [Kra19]. Figure 5 displays the relationship between the stopping voltage corresponding to light at different frequencies. This data and fit result clearly show a direct causation of higher frequency of light resulting in a higher observed stopping voltage which disagrees with the predictions associated with the wave theory of light.

The third observed characteristic of the photoelectric effect is that the first photoelectrons are emitted virtually

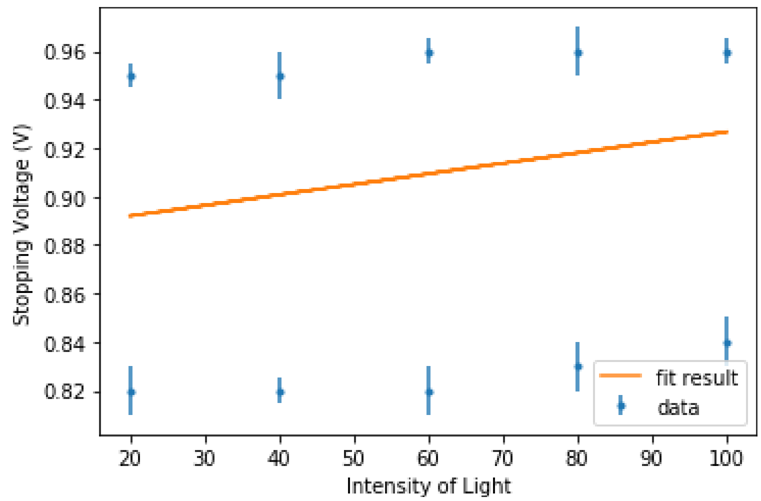

Figure 4: Plot of the observed results of the effect the light source's intensity has on the stopping voltage.

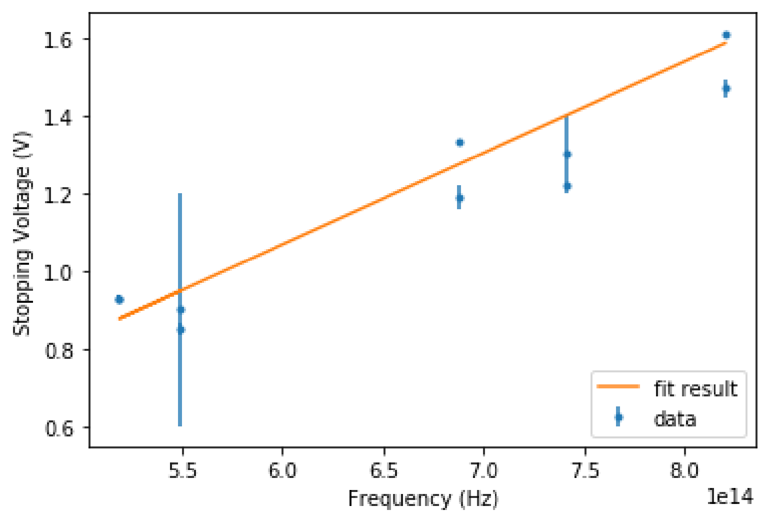

Figure 5: Plot of the observed results of the effect the light source's frequency has on the stopping voltage.

instantaneously (within 10^{-9} s) after the light source is turned on [Kra19]. This also disagrees with the delay predicted by the classical wave theory.

3 Theoretical Explanation

In the year 1900, the German physicist Max Planck had developed a theory, known as the Quantum theory, to explain the wavelength distribution of light emitted by hot and glowing objects (called thermal or blackbody radiation)[Kra19]. In his quantum theory, Planck provides an expression for the intensity of electromagnetic radiation coming from objects at different temperatures. This expression relies a proportionality constant defining the quantum chunk size of energy associated with an electromagnetic wave. Based on Planck's ideas with thermal radiation, Albert Einstein developed a successful theory of the photoelectric effect in 1905. He proposed that the energy of electromagnetic radiation is not continuously distributed over the wave front, but is instead concentrated in localized bundles or *quanta* (also known as *photons*). The energy of a photon associated with and electromagnetic wave frequency f is $E = hf$ where h is the proportionality constant yielded by Planck's theory of thermal radiation known as *Planck's constant*.

The Photon energy can also be related to the wavelength of the electromagnetic wave by substituting $f = \frac{c}{\lambda}$, which gives $E = \frac{hc}{\lambda}$.

In Einstein's interpretation, a photoelectron is released as a result of an encounter with just one photon. The entire energy of the photon is delivered instantaneously to a single photoelectron. If the photon energy hf is greater than the work function ϕ of the material, the photoelectron will be released. If the photon energy is smaller than the work function, the photoelectric effect will not occur. This explanation thus accounts for two of the failures of the wave theory: the effect of frequency on the stopping voltage and the lack of any measurable time delay. If the photon energy hf exceeds the work function, the excess energy appears as the kinetic energy of the electron: $K_{max} = hf - \phi$ [Kra19]. The intensity has no part in this maximum kinetic energy expression. For a fixed frequency, doubling the intensity of light means that twice as many photons strike the surface and twice as many photoelectrons are released, but they all have the same maximum kinetic energy, resulting in the same stopping voltage. A photon that supplies an energy equal to ϕ, exactly the minimum amount needed to remove an electron, corresponds to light of frequency equal to the cutoff frequency f_c. At this frequency, there is no excess energy for kinetic energy so $K_{max} = hf - \phi$ becomes $\phi = hf_c$ under these circumstances. This also means the cutoff frequency can be expressed as $f_c = \frac{\phi}{h}$. The corresponding cutoff wavelength is $\lambda_c = \frac{c}{f_c}$ or $\lambda_c = \frac{hc}{\phi}$. The cutoff wavelength represents the largest wavelength for which the photoelectric effect can be observe for a surface with the work function ϕ [Kra19].

Einstein's photon theory appears to explain all of the observed features of the photoelectric effect. The most detailed test of the theory was done by Robert Millikan in 1915 [Kra19]. He measured the maximum kinetic energy (stopping voltage) for different frequencies of the light and obtained a plot the expression $K_{max} = hf - \phi$. See Figure 6. From the slope of the fit line in blue, Millikan obtained a value for Planck's constant of $h = 6.57 \times 10^{-34}$ J s. After a variety of experiments, the value of Planck's constant has been measured with great precision ans has a presently accepted value of $h = 6.626\,070\,4 \times 10^{-34} \pm 1 \times 10^{-8}$ J s.

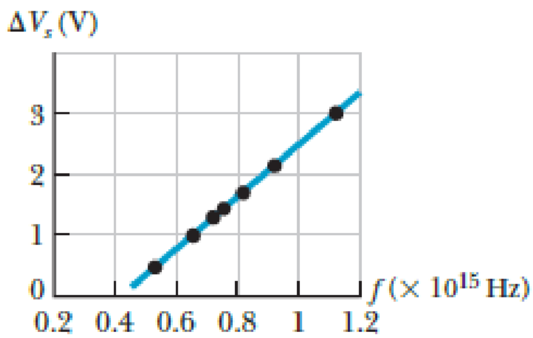

Figure 6: Robert A. Millikan's results for the photoelectric effect in sodium.

4 Implications

The successful quantum theory which was developed to explain the observations of the photoelectric effect has impacted the way scientists understand light and its interactions with the world. There are many applications that resulted from the photoelectric effect's work. Light is now understood to hold the duality characteristic of being both a particle, as a photon, and a an electromagnetic wave. As photons are thought of as concentrated chunks of energy they have particle-like properties and like Electromagnetic waves, photons travel at the speed of light. From this, scientists such as Albert Einstein have developed mathematical constructs such as the momentum of a photon. With concepts of light having momentum developed The world of interactions between photons and other atomically small particles birthing the field of quantum physics. Engineering of technology has benefited from the understanding of the photoelectric effect. For instance, solar panels, imaging technology, including older television camera tubes or image intensifiers and many more complex and fine-tuned machinery has been developed because of the photoelectric effect and our understanding of it.

References

[Kra19] Kenneth S Krane. *Modern physics*. John Wiley & Sons, 2019.

[SD16] Kenneth R Spring and Michael W Davidson. Light: Particle or a wave? https://micro.magnet.fsu.edu/primer/lightandcolor/particleorwave.html, 2016.