The Photoelectric Effect

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Introduction

One of the most critical endeavors in the history of modern science was the study of the photoelectric effect during the early 20th century. Experiments observing the effects of this process both led to and proved definitively Albert Einstein's particle (or quantum) theory of light. Thus, in many ways it marked the first step toward a new era in physics, when quantum mechanics would supersede classical mechanics and radically change our understanding of the very small and the reality they constitute.

The photoelectric effect is the ejection of electrons from a material (typically a metal surface) when light is shone upon it (see Fig. 1). This is the process that allows us to generate electricity using photovoltaic solar panels. The effect was first observed by Heinrich Hertz in 1886, who found during one of his experiments that electrodes spark more vigorously when illuminated with ultraviolet light. It wasn't understood exactly what was happening until J.J. Thomson explained in 1899 that the light was causing electrons (which he had recently discovered) to escape from the atoms in the metal. The most interesting thing about the photoelectric effect, however, was discovered by Philipp Lenard in 1902—the fact that the **energy of the photoelectrons depends only on the frequency (or color) of the light, not on the intensity (or brightness).**

*Note: Lenard was unable to quantitatively determine the relationship between the stopping voltage and the frequency of the light—this data would come later with Robert Millikan's research.

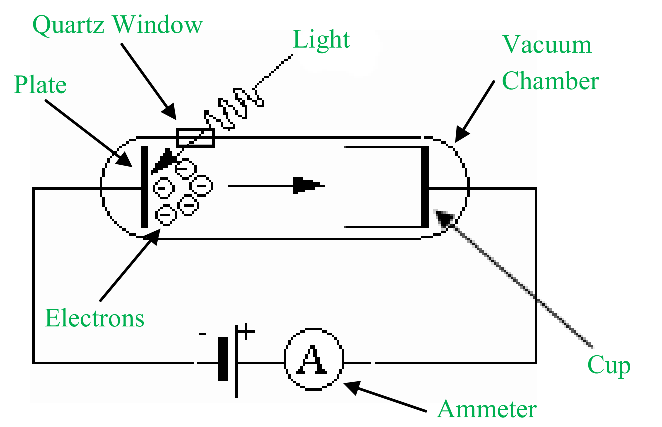


Fig. 2. Experimental apparatus. The circuit creates an electric potential between the plate and the cup that resists the motion of the photoelectrons.

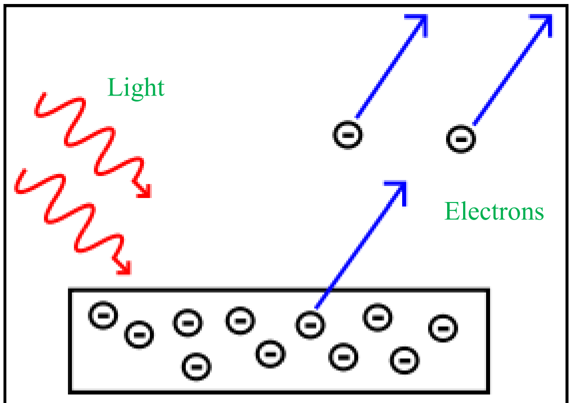


Fig. 1. The photoelectric effect. Electromagnetic radiation strikes a surface, "knocking" electrons in the material out of their atomic orbitals.

A Conundrum

The experiment in which Lenard proved this fact involved an apparatus similar to the one shown in the figure above (Fig. 2). In this setup, a metal plate and cup are placed in a vacuum inside a glass container and light is shone through a quartz window onto the plate. This, in turn, creates photoelectrons that are collected by the cup. The number of electrons that reach the cup is represented by the resulting electric current (the rate of flow of electrons through a wire), which is measured by the ammeter connected to the circuitry. Then, an electric potential (or voltage) is applied between the plate and the cup such that the motion of the photoelectrons towards the cup is resisted (i.e. if a single, motionless electron were placed in the area between the plate and the cup, it would move to the plate). By this method, if the potential is gradually increased, at some point the current measured by the ammeter will drop to zero, which indicates that all of the electrons emitted from the plate stayed at the surface of the plate and were not able to make it to the cup. In other words, they have no motion, or kinetic energy. Thus, by the relation:

$$E = qV$$

Where E is energy, q is charge, and V is potential, we know that the kinetic energy (the energy of motion) of the fastest-moving electron (i.e. the electron with the most kinetic energy) is equal to the charge of an electron (e) times the potential at which the current became zero, which is called the stopping potential (V_0).

$$K_{max} = eV_0$$

Contrary to expectation, Lenard found that the stopping potential (and thus the maximum kinetic energy of the photoelectrons) changed as the wavelength/frequency of the light illuminating the plate was changed, not as the intensity was changed*. Indeed, there was some frequency below which the stopping potential was always zero regardless of intensity—this is called the cutoff frequency (ν_0).

Light—What Is It?

To understand why this result was so surprising, more knowledge is required about how light was perceived before Einstein's particle theory came about. It was established in 1864 by James Clerk Maxwell that electricity, magnetism, and light are all facets of the same phenomenon. Visible light, as well as radio waves, microwaves, and x-rays (among others), are all electromagnetic waves. The only difference between light that humans can see and deadly gamma radiation is the wavelength/frequency of the waves (see Figures 3 and 4 below). Since we know that light is a wave, we have every reason to believe that the energy of a beam of light corresponds to the amplitude (or height) of its component waves, which should be able to take any value from zero to infinity. Picture a surface of water: there can be no wave and the water is perfectly still (corresponding to zero energy), there can be a very large wave (lots of energy), or there can be any size wave in between. Thus, by increasing the amplitude/intensity of the light shining on the metal, we should be able to change the energy of the emitted photoelectrons. This, of course, contradicts Lenard's findings.

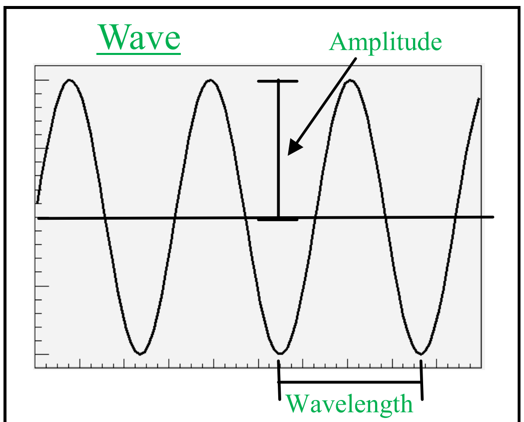


Fig. 3. All electromagnetic radiation takes the form of a wave. The frequency is the number of wave cycles per unit time, so a longer wavelength equates to a smaller frequency.

Einstein to the Rescue

It was Einstein who offered an explanation in 1905. Building on the earlier work of Max Planck, he suggested that light is actually a particle, a bundle of energy that later came to be known as the photon. This means that the energy of a beam of light can only come in multiples of the photon that makes it up—in other words, light energy (or radiant energy) is quantized (this is where the phrase quantum mechanics comes from). The energy of a photon itself, Einstein proposed, is directly related to the wavelength/frequency of the light by the equation:

$$E = h\nu$$

Where E is the photon energy, ν is the light frequency, and h is Planck's constant, a number that Planck estimated in 1899 while he was working on blackbody radiation. Einstein also assumed that, when a photon in a beam of light strikes a metal surface, all of its energy is transferred to a single electron that it collides with. Thus, the kinetic energy of a photoelectron is equal to the energy of the photon that collides with it minus the energy that is required to remove it from the metal.

$$K = h\nu - w$$

In the case of the electron that is easiest to remove from the metal,

$$K_{max} = h\nu - w_0$$

Where w_0 is called the work function of a given material. By this reasoning, if the photons in a beam of light do not have more energy than the work function of the metal surface that the beam is striking, no electrons will be ejected (in the case that $h\nu = w_0$, electrons will be removed from the metal but they will then be motionless because their kinetic energy is zero). This explains why it is the frequency that determines the energy of photoelectrons as well as whether or not any electrons are ejected at all. Light of greater intensity corresponds to a greater number of photon-electron collisions (because the photon density of the light is greater), but no matter how many photons bombard an electron, the electron will only escape if it collides with a photon of sufficient energy. This is why, for most metals, red light of great intensity will never cause any photoelectrons to be emitted, whereas ultraviolet light of much lesser intensity will (see Fig. 5 on page 3).

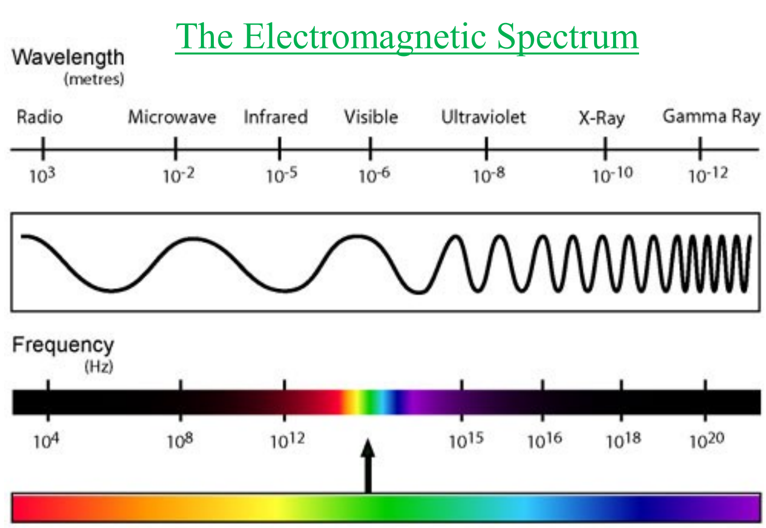


Fig. 4. The entire spectrum of electromagnetic radiation. Notice the range of frequencies in which visible light exists.

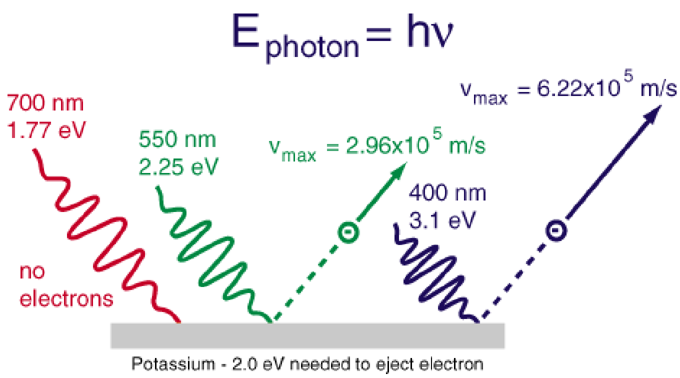


Fig. 5. For potassium, no electrons are emitted when the incident light is red. When green light strikes the metal, however, the photons have enough energy to create photoelectrons. The photoelectrons have even more kinetic energy (that is, they move faster) when the frequency is increased further to violet light.

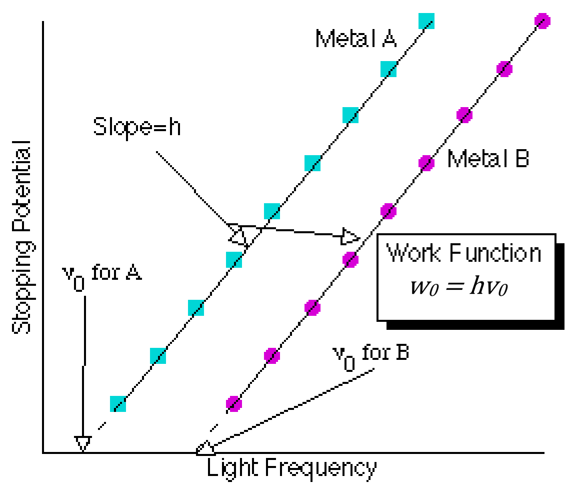


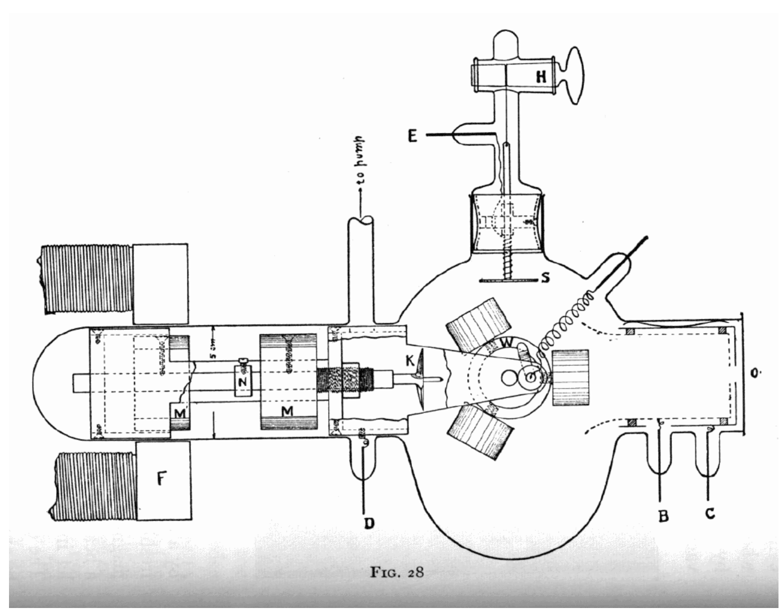
Fig. 6. Plots of stopping potential vs. light frequency for two different metals. The data forms straight lines, indicating a direct relationship between the two variables. ν_0 is the cutoff frequency, below which no photoelectrons will be emitted. The slope of each line is equal to Planck's constant.

Proof

Einstein's explanation was confirmed experimentally in 1914 by a scientist who had initially set out to disprove it, Robert Millikan. Millikan refused to believe Einstein's theory because it contradicted the well-established wave theory of light. After a decade of work, however, he was forced to concede that Einstein's idea was the only explanation that fit his experimental results. Millikan performed a quantitative study of the photoelectric effect, accurately measuring the stopping potential at various frequencies for many different materials. He found a direct relationship between these two quantities, as shown by the graph on the left (Fig. 6). This proved Einstein's assertion that light comes in quantized bundles of energy that are directly proportional to the light frequency ($E = h\nu$). He also measured h (the proportionality constant, i.e. the slope of the line on the graph) to be 6.57×10^{-34} Joule-seconds ±0.5% for all the materials he tested. Planck's original estimation for the value of h was 6.63×10^{-34} Joule-seconds, and the currently accepted value is 6.6262×10^{-34} Joule-seconds. Einstein and Millikan each received a Nobel Prize for Physics (Einstein in 1921 and Millikan in 1923) for their respective work on the photoelectric effect.

Where Does All This Leave Us?

In sum, the photoelectric effect provided scientists with the evidence they needed to completely revolutionize physics. Studies of this effect proved that electromagnetic radiation has a particle nature, culminating in the idea of the wave-particle duality of light. Eventually, this duality principle would be extended from photons to all forms of energy, including matter. The result was quantum field theory, which sent science as a whole in wildly new directions and today is the primary lens through which physicists view the universe.



Millikan's apparatus, used to study the photoelectric effect.

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