

The Photoelectric Effect

If the conditions are right, a beam of light can knock electrons out of the surface of a metal. When the effect was first discovered, one of the most striking things about it was that it could not be explained by the classical theory of electromagnetism, the only available theory of light at the time.

Firstly, we will define a few terms. The electrons emitted from the surface are called *photoelectrons*. If the frequency of the light is swept, we find that there is a minimum frequency ν_0 below which no electrons are emitted. The energy $h\nu_0$ corresponding to this frequency is called the *work function* of the surface, and is often given the symbol ϕ . In experiments used to investigate the photoelectric effect, the photoelectrons are usually collected on a metal plate detector, which forms part of an electrical circuit. The current measured in the circuit is proportional to the number of electrons striking the detector plate. To measure the kinetic energy of the electrons, we can apply a static potential V_r (often known as a *retarding potential*) to the plate. Only electrons with a kinetic energy greater than eV_r , where e is the electronic charge, will reach the plate; any electrons with a kinetic energy less than eV_r will be repelled, and won't be detected. The *stopping potential*, V_0 , is the retarding potential at which no more electrons are detected, and tells us the kinetic energy of the fastest electrons i.e. $K_{\max}=eV_0$. One of the important early observations about the photoelectric effect is that for a particular metal surface and frequency of light, the stopping potential is independent of the light intensity.

Now we will look at why classical electromagnetism fails to explain the photoelectric effect, and why all the problems are solved by quantum mechanics.

1. Light intensity

In classical electromagnetism, increasing the intensity of a beam of light increases the amplitude of the oscillating electric field vector \underline{E} . Since the force that the incident beam exerts on an electron is $e\underline{E}$, the theory would predict that the energy of the photoelectrons would increase with increasing light intensity. However, this is not the case: V_0 is *independent* of light intensity. In quantum mechanics however, doubling the intensity simply doubles the number of photons, it does not change their energy. If the photoelectric effect is interpreted as a collision between a single photon and an electron in the metal surface, then the total number of photons striking the surface is immaterial in determining the energy of the ejected electron.

2. Frequency

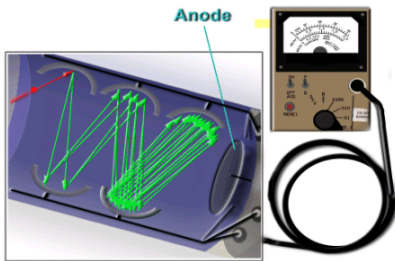
According to classical electromagnetism, as long as the *intensity* of the light is great enough, the photoelectric effect should occur at any frequency, a direct contradiction of the experimental evidence, which shows a clear cutoff frequency below which no electrons are ejected. In quantum mechanics the frequency of the light determines the photon energy, and since it takes a certain minimum amount of energy to knock an electron out of the surface (defined by the work function ϕ of the surface), photons with energy $h\nu < \phi$ simply do not have enough energy to achieve this.

3. Time delay

In classical electromagnetism the energy imparted to the electron must somehow be 'soaked up' from the incident wave. Since this takes some time, if very weak light was used it would be expected that there should be a measurable time delay between the light striking the surface and the electron being emitted. This has never been observed. In quantum mechanics, the photoelectric effect is viewed as a single collisional event and no time delay is predicted.

In addition to providing one of the early proofs of quantum mechanics, the photoelectric effect also has a number of highly useful practical applications. One example is solar panels. These are generally a series of metallic plates that face the sun. They emit electrons when struck by sunlight, which are used to produce electrical power.

The photoelectric effect is also widely used in sensitive light detectors for scientific experiments. In a photomultiplier tube (PMT), light strikes a photosensitive cathode, causing it to emit electrons through the photoelectric effect. These electrons are accelerated towards a second



cathode, producing further electrons, which are accelerated towards a third electrode, and so on. The result is that a few photons striking the initial cathode are multiplied into millions of electrons, which can be detected as a current pulse at the last plate (called the 'anode'). PMTs have applications in detecting photons emitted from excited state atoms and molecules (many emission spectroscopy experiments rely on a PMT to detect the signal), or produced in the types of collisions studied in high energy physics.

Yet another application is the 'photoelectric cell', or 'photocell', a device whose electrical characteristics (current, voltage, resistance etc) vary when light is incident upon it. The current from a photocell can easily be used to operate switches or relays, which has led to applications in light activated counters, automatic door openers and intrusion alarms (in these types of devices, photocells are sometimes known as 'electric eyes').