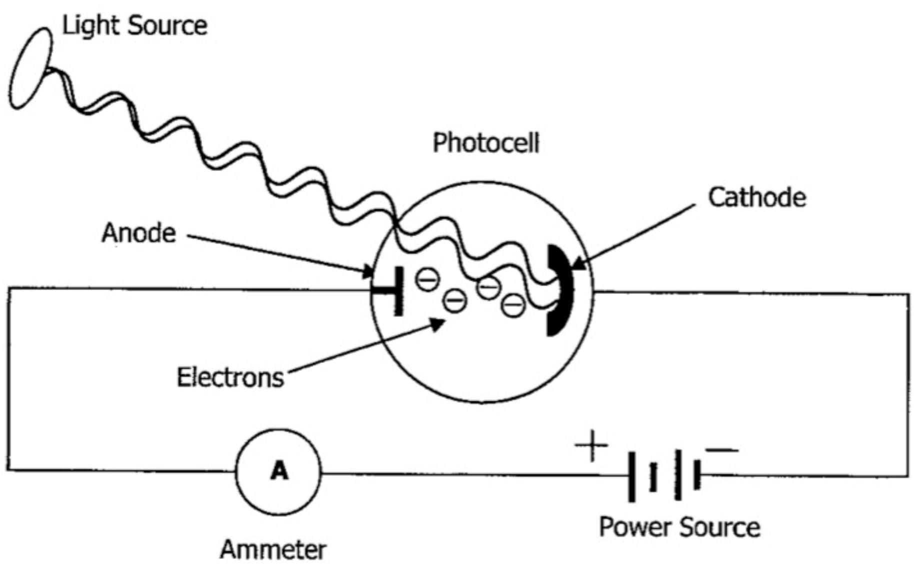
The Photoelectric Effect

The **photoelectric effect** is the ejection of electrons from the surface of a metal by light. The photoelectric effect can be studied using a photocell, such as the one shown below.



The cell has two metal electrodes sealed in an evacuated tube. The air has been removed to keep the metal surface clean and to keep electrons from being stopped by the air molecules. The large electrode, the cathode, is usually coated with cesium or some other alkali metal. The second electrode, the anode, is made of a thin wire so it does not block any radiation. The tube is often made of quartz to permit ultraviolet wavelengths to pass through.

A power source is connected to the anode and the cathode in such a way that the negative side of the source is attached to the cathode and the positive side is connected to the anode. An ammeter can measure if there is a current flowing through the circuit.

When no radiation falls on the cathode, the current does not flow in the circuit. When radiation does fall on the cathode, a current is produced in the circuit and this is indicated by the ammeter. The current is a result of electrons, called photoelectrons, being ejected from the cathode by the radiation. The electrons then move to the anode.

The Photoelectric Effect and the Wave Theory

According to the wave theory of light, the energy carried by light depends only on the amplitude of the wave – that is, on the intensity of the light (how bright it is). Other factors, such as the frequency (color) of the light should not affect its energy.

In order to eject electrons from a metal, the light must transfer a sufficient amount of energy to the electrons. If the light is too dim, no electrons should be ejected. As the intensity of the light increases, more electrons should be ejected and those electrons should be moving faster. This should occur regardless of the frequency of light. So, red light and blue light of equal intensity should eject the same number of electrons, with the same average speed.

The Photoelectric Effect and the Particle Model

In 1905, Albert Einstein published a revolutionary theory that explained the photoelectric effect. Einstein proposed that the energy of light is not transmitted as a wave. Rather, it is concentrated in discrete bundles of energy called **photons**.

He proposed that the amount of energy in each photon was a discrete, fixed amount that depended directly on the frequency of the light. The higher the frequency, the greater the energy contained in the photon.

Based on Einstein's theory, it is the frequency (color) of the light that determines whether or not it will eject electrons from a metal. In order to eject electrons from a metal, light must have a certain minimum frequency, known as the threshold frequency, f_0. If the frequency of the light is less than f_0, no electrons will be ejected regardless of how bright the light is. If the frequency is higher than f_0, the excess energy is converted to kinetic energy of the moving electron.

For light whose frequency is equal to or greater than f_0, the intensity of the light will determine how many electrons are ejected. Light with a greater intensity will eject more electrons.

Notice that an electron cannot simply accumulate photons until it has enough energy. Only one photon interacts with one electron. The photon either has enough energy to eject the electron or it does not.

Summary

The wave theory predicted that light must have sufficient intensity to eject electrons, and that light of higher intensity should eject more electrons than light of lower intensity, regardless of the frequency of the light.

The particle theory predicted that light must have a sufficiently high frequency to eject electrons. Light whose frequency was too low would not eject electrons, regardless of its intensity.

It has been determined through experiment that the particle theory's explanation is correct.

Comparing the Wave Model and the Particle Model

What follows is a quick summary of the behaviors of light, and which model provides a better explanation of each behavior.

Reflection
Newton's model adequately explained reflection, but gave a weak explanation of partial reflection and partial refraction. The wave model gave a satisfactory explanation of both. Thus, the wave model better explains reflection.

Refraction
The particle model predicted that light would be faster in water than in air. The wave model predicted light would be faster in air than in water. The wave model was correct, and so better explains refraction.

Diffraction
Newton claimed that light did not diffract, which appeared to be true base on what was observable in his time. Later evidence, however, has shown that light does indeed diffract provided the opening through which it passes is very, very small. Since waves diffract and particles don't, the wave model provides a better explanation here as well.

Interference
Young's experiment verified that light does interfere, provided that:

1. You use monochromatic light (preferably in phase).
2. The separation of the two slits must be very small.

The interference of light is clear evidence that light is a wave.

Photoelectric Effect
The wave model predicts that the intensity of light should determine whether or not electrons are ejected from a metal (frequency should have no effect). The particle model predicts that this should be determined by frequency, rather than intensity.

Experiments have shown that the particle model correctly explains this behavior.

The Principle of Complementarity and Light

It has become obvious that neither the wave model nor the particle model can explain all the behaviors of light. Instead, physicists have decided that light has a dual nature, known as **wave-particle duality**.

Niels Bohr (1885-1962) summarized this dual nature in his **Principle of Complementarity**. He stated that: "Understanding both the wave and the particle properties of light is essential if one is to have a full understanding of light. In other words, the two aspects of light complement each other."

As a general rule, when light passes through space or through a medium, its behavior is best explained using its wave properties. But when light interacts with matter, its behavior is more like that of a particle.