15.6.1: Photoelectric Effect

In 1887, a German physicist named Heinrich Hertz was working with radio waves, when he discovered that light could be used to eject electrons from metal surfaces. The ejected electrons were called *photoelectrons* to link them to this specific behavior, which was dubbed the *photoelectric effect*.

In order to ionize an atom and cause the electron to be ejected a certain amount of energy has to be provided, called the electron binding energy. The classical model suggested that the rate at which energy was provided was unimportant. A little bit of energy over a long time period should work as well as a lot of energy over a short time period. The expectation was that if small amounts of energy were provided there should be a lag, or delay, before the photoelectron appeared. This was not supported by the evidence. A second prediction of the classical model was that more intense waves should give the electrons more kinetic energy, and that the color (wavelength) of the light used should not matter.

However, the results were strongly dependent on the wavelength and not at all dependent on the intensity. In fact, there were no photoelectrons at all above a certain wavelength. This made no sense in the classical model, and it was the work of Albert Einstein in 1905 that led to a consistent explanation. Einstein reasoned that Planck model of quantized energy could explain this seemingly bizarre behavior. He extended Planck's hypothesis to suggest that electromagnetic waves were actually a 'swarm' of quanta, meaning that the wave itself is quantized. An analogy might be to look at a school of fish, or a flock of birds. Each one is a separate entity, but the entire collective moves as a single unit.

Einstein called each unit of the wave a *photon.* An individual photon moves at the speed of light (c). A light 'wave' is a collection of photons, each of which has a particular frequency. The energy of a photon is quantized:

$$E_f = hf = \frac{hc}{\lambda}$$

Because Planck's oscillators can only receive or emit energy that is a multiple of their oscillation frequency, a photon with the wrong wavelength (frequency) will not eject an electron. Photons of the correct frequency (or integer multiples of the correct frequency) will transfer their energy to the electron, causing it to be ejected. This "all or nothing" approach to energy transfers is a hallmark of quantum phenomena. In this model, an intense electromagnetic wave is composed of a large number of photons, so 'bright' light means a large photon number and 'dim' light is the result of fewer photons. The photon model also explained why there were no photoelectrons above a certain wavelength. If the wavelength was too long, the frequency would be too low and the photons would not have enough energy to eject an electron. Since an electromagnetic wave could transfer momentum, each individual photon also had to have momentum. The momentum of a photon could be written as follows:

$$p = \frac{h}{\lambda}$$

Einstein's photon model accounted for all the effects that the classical model could not. It suggested that the Planck hypothesis was not simply a mathematical trick and energy quantization was apparently the correct way of looking at the world. In some ways, this idea should be somewhat familiar. After all, a stream of water is composed of huge numbers of water molecules. A sand dune is a pile of trillions of sand grains. A squirrel is an aggregate of different cells. At a large scale, these seem like continuous objects because we cannot see the details but as we 'zoom in' a new picture emerges.

These and other experiments that could be best explained by the photon model helped cement the idea of energy quantization. This would form the basis for the Bohr model of the atom and explain the colors emitted by different types of atoms, eventually allowing us to determine the atmospheric composition of distant planets. The ideas surrounding quantization would eventually give rise to Quantum Mechanics, which is a branch of physics focusing on the behaviors of very small numbers of very small objects. This branch of physics gave rise to semiconductors and are used on a daily basis in many devices, including the memory of your smart phone.