4.1: Light as a Stream of Particles

Although the first suggestion that light acts as a particle rather than a wave can be dated to Planck's explanation of blackbody radiation, the explanation of the photoelectric effect by Einstein is both simple and convincing. In the photoelectric effect, a beam of light is directed onto a metal plate. It had been noted that the energy deposited by the light on the plate is sufficient (under certain circumstances) to free electrons from the plate.

The energy of the freed electrons (measured by the voltage needed to stop the flow of electrons) and the number of freed electrons (measured as a current) could then be explored as a function of the intensity and frequency of the incident light. These early experiments revealed several surprises:

- The energy of the freed electrons was independent of light intensity. Thus, even when the energy per second striking the plate increased, the electrons did not respond by leaving the plate with more energy, nor when an extremely weak light was used were the electrons emitted with less energy. If light is a wave, a more intense wave should deposit more energy to each electron.
- Below a certain frequency (the threshold frequency) no electrons were emitted, regardless of light intensity. Thus, an extremely bright red light, for example, would free no electrons while an extremely faint blue light would. In fact, as the frequency increased, the electron energy increased proportionally. If light is a wave, all frequencies should emit electrons since at all frequencies enough light would ultimately be deposited on the electron.
- The electrons were emitted the instant (within 10-9 s) the light struck the metal. If the energy in the light was distributed over some spatial volume (as it is in a wave) a small time lag should occur before the electrons are emitted, since a small amount of time is necessary for the electron to "collect" enough energy to leave the metal.

Einstein realized that all of these "surprises" were not surprising at all if you considered light to be a stream of particles, termed *photons*. In Einstein's model of light, light is a stream of photons where the energy of each individual photon is directly proportional to its frequency

$$E_{photon} = hf \tag{4.1.1}$$

where f is the frequency and h is Planck's constant, $6.626 \times 10^{-34}\ J\,s$, introduced several years earlier. This model resolves all of the issues raised by the photoelectric effect experiments:

- A more intense light source contains more photons, but each individual photon has exactly the same energy. Since the electrons are freed by absorbing individual photons, every electron is freed with exactly the same energy. Increasing intensity increases the *number* of photons and hence the *number* of free electrons, but not their individual energy.
- Below a certain frequency the individual photons in the light beam do not have enough energy to overcome the bonds holding the electrons in the metal. Regardless of the number of photons, if each individual photon is too "weak" to free an electron, no electrons will ever be freed.
- The energy in the light beam is not spread over a finite spatial volume; it is concentrated into individual, infinitesimal bundles (the photons). as soon as the light strikes the metal, photons strike electrons, and electrons are freed.

For his explanation of the photoelectric effect in terms of photons, Einstein was awarded the Nobel Prize in 1921.

The Photoelectric Effect

A metal is illuminated with 400 nm light and the stopping potential is measured to be 0.87 V.

a. *What is the workfunction for the metal?*
b. *For what wavelength light is the stopping potential 1.0 V?*

Applying energy conservation to the photoelectric effect results in a relationship for the kinetic energy of the ejected electrons. The incoming energy is in the form of photon energy. Some of this energy goes toward freeing the electrons from the metal surface (this "binding" energy of the electrons to the surface is called the workfunction, ϕ) while the remainder (if any) appears as kinetic energy of the ejected electrons. Therefore,

$$E_{photon} = \psi + KE_{electrons} \tag{4.1.2}$$

or

$$KE_{electrons} = E_{photon} - \psi \tag{4.1.3}$$

In Einstein’s model of the photon the energy of a photon is given by

where f is the frequency and the wavelength of the light, and h is Planck’s constant, 6.626 x 10-34 Js. A more useful factor, with more “friendly” units, is
hc = 1240 eV nm.
Combining this with the result from energy conservation yields

Additionally, the electrons can be “stopped” by the application of an appropriately biased potential difference. The electron current will stop when the maximum kinetic energy of the electrons is matched by the electrostatic energy of the potential difference. This potential difference is termed the stopping potential, and is given by

Therefore, in part a, if the stopping potential is 0.87 V, then the maximum kinetic energy of the emitted electrons must be 0.87 eV. So,

In part b, if the stopping potential is measured to be 1.0 V, then the wavelength of the incident light must be

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