2.2 Taking Quanta Seriously

In 1905, Albert Einstein used the idea of quanta to explain the photoelectric effect, which was described by Philipp Lenard (1862-1947). The photoelectric effect occurs when light shines on a metal plate and electrons are ejected, creating a current.[8] Scientists had established that there is a relationship between the wavelength of the light used, the type of metal the plate is made of, and whether or not electrons are ejected. It turns out that there is a threshold wavelength (energy) of light that is characteristic for the metal used, beyond which no electrons are ejected. The only way to explain this is to invoke the idea that light comes in the form of particles, known as photons, that also have a wavelength and frequency (we know: this doesn't make sense, but bear with us for now). The intensity of the light is related to the number of photons that pass by us per second, whereas the energy per photon is dependent upon its frequency or wavelength, because wavelength and frequency of light are related by the formula $\lambda\nu = c$ where c is the speed of light in a vacuum, is a constant and equal to $\sim 3.0 \times 10^8 \mathrm{m/s}$. The higher the frequency ν (cycles per second, or Hertz), the shorter the wavelength λ (length per cycle) and the greater the energy per photon. Because wavelength and frequency are inversely related–that is, as one goes up the other goes down– energy is directly related to frequency by the relationship $\mathrm{E} = h\nu$ or inversely related to the wavelength $\mathrm{E} = \frac{hc}{\lambda}$, where h is Planck's constant. So radiation with a very short wavelength, such as x rays ($\lambda = \sim 10^{-10} \mathrm{m}$) and ultraviolet light (between 10^{-7} to $10^{-8} \mathrm{m}$), have much more energy per particle than long wavelength radiation like radio and microwaves ($\lambda = \sim 10^3 \mathrm{m}$). This is why we (or at least most of us) do not mind being surrounded by radio waves essentially all the time yet we closely guard our exposure to gamma rays, X-rays, and UV light; their much higher energies cause all kinds of problems with our chemistry, as we will see later.

Because of the relationship between energy and wavelength ($\lambda\nu = c$), when you shine long-wavelength, low energy, such as infrared, but high intensity (many photons per second) light on a metal plate, no electrons are ejected. But when you shine short-wavelength, high energy (such as ultraviolet or x rays) but low intensity (few photons per second) light on the plate, electrons **are** ejected. Once the wavelength is short enough (or the energy is high enough) to eject electrons, increasing the intensity of the light now increases the number of electrons emitted. An analogy is with a vending machine that can only accept quarters; you could put nickels or dimes into the machine all day and nothing will come out. The surprising result is that the same **total** amount of energy can produce very different effects. Einstein explained this observation (the photoelectric effect) by assuming that only photons with "enough energy" could eject an electron from an atom. If photons with lower energy hit the atom no electrons are ejected – no matter how many photons there are.[9] You might ask: Enough energy for what? The answer is enough energy to overcome the attraction between an electron and the nucleus. In the photoelectric effect, each photon ejects an electron from an atom on the surface of the metal. These electrons exist somewhere within the atoms that make up the metal (we have not yet specified where) but it takes energy to remove them and the energy is used to overcome the force of attraction between the negative electron and the positive nucleus.

Now you should be really confused, and that is a normal reaction! On one hand we were fairly convinced that light acted as a wave but now we see some of its behaviors can be best explained in terms of particles. This dual nature of light is conceptually difficult for most normal people because it is completely counter intuitive. In our macroscopic world things are either particles, such as bullets, balls, coconuts, or waves (in water); they are not—no, not ever—both. As we will see, electromagnetic radiation is not the only example of something that has the properties of both a wave and a particle; this mix of properties is known as wave–particle duality. Electrons, protons, and neutrons also display wavelike properties. In fact, all matter has a wavelength, defined by Louis de Broglie (1892–1987), by the equation $\mathrm{E} = \frac{h}{mv}$ where mv is the object's momentum (mass $\times$ velocity) and h is Planck's constant. For heavy objects, moving at slow speeds, the wavelength is very, very small, but it becomes a significant factor for light objects moving fast, such as electrons. Although light and electrons can act as both waves and as particles, it is perhaps better to refer to them as quantum mechanical particles, a term that captures all features of their behavior and reminds us that they are weird! Their behavior will be determined by the context in which we study (and think of) them.