1.1.4: Wave-Particle Duality

Wave Particle Dualism

The phenomenon of the wave-particle dualism was first discovered for electromagnetic radiation, and the extended to all other particles including the electron. It began with the investigation of the photoelectric effect by Albert Einstein (Fig. 1.2.1 and Fig. 1.2.2).

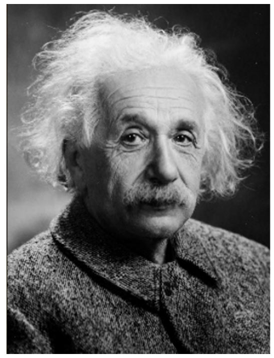

Figure 1.2.1 Albert Einstein, Nobel Prize 1921. (Attribution: Photograph by Orren Jack Turner, Princeton, N.J. Modified with Photoshop by PM_Poon and later by Dantadd. [Public domain], commons.wikimedia.org/wiki/F...lanck_1933.jpg)

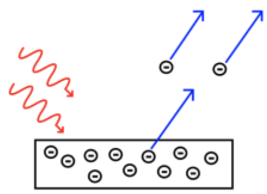

Figure 1.2.2 The photoelectric effect (Attribution: Wolfmankurd [CC BY-SA (http://creativecommons.org/licenses/by-sa/3.0/)]. commons.wikimedia.org/wiki/F...ric_effect.svg)

The photoelectric effect occur when a metal surface is irradiated by light. Above a certain frequency, or below a certain wavelength, light is able to eject electrons from the metal surface. The threshold frequency depends on the metal. Below the threshold frequency no electrons get ejected. Einstein investigated the maximum kinetic energy of the ejected electrons as a function of the frequency of the light. He found that there was a linear relationship. He analyzed the slope of this line and found that the slope was the Planck constant h. This would mean that electrons had an energy $E=h\nu$ minus an energy E_B that would be needed to overcome the binding energy, also called the work function, of the electron in the metal (Figure 1.2.3, left).

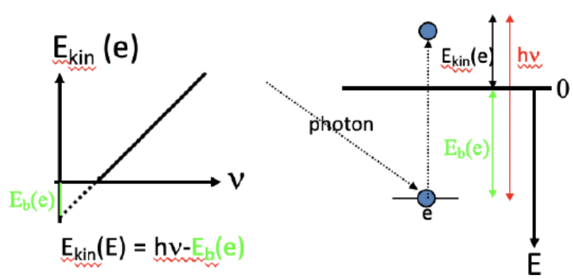

Figure 1.2.3 Maximum kinetic energy of the ejected electron as a function of the frequency of light (left), and mechanistic interpretation of the photoelectric effect (right).

The equation $E=h\nu$ was previously derived by Planck (Fig. 1.2.4) based on the assumption that energy was quantized, and now Einstein had experimentally found it again in the quest to explain the photoelectric effect. This would mean that light was quantized. The quantization would be explained by the fact that light would not only have wave but also particle properties, and these particles would be called photons. Assuming photons the photoelectric effect could be easily explained (Figure 1.2.3, right). When light hits the metal surface the photon collides with the electron. Only when the photon had an energy larger than the work function of the metal, the electron would be ejected and would have a kinetic energy equal to the difference between the energy of the photon and the binding energy. The wave-particle dualism of light, and electromagnetic radiation in general can also be mathematically derived. Because mass can be converted into electromagnetic radiation according to the equation $E = mc^2$, and the energy of electromagnetic radiation is $E=h\nu$, $mc^2=h\nu$. We can solve the equation for ν, and then it is $\nu=mc^2/h$. With $\nu=c/\lambda$, and solved for λ, the equation becomes $\lambda=h/mc$. This equation shows the wave particle-dualism of electromagnetic radiation because it relates a wavelength to a mass. In fact, the mass of the particle associated with electromagnetic radiation, the photon, is inverse proportional to the wavelength of the electromagnetic radiation. The discovery of the wave-particle dualism of electromagnetic radiation was a radically new concept that is difficult to grasp intellectually up to this date because the human mind tends to see waves and particles to be mutually exclusive. However, it is one of the most fundamental principles of nature. As we will see later, not only electromagnetic radiation shows the wave particle dualism, but all particles including electrons.

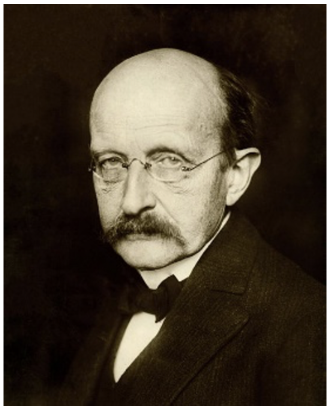

Figure 1.2.4 Max Planck, Nobel Prize 1918 (Attribution: commons.wikimedia.org/wiki/F...lanck_1933.jpg)

Wave Particle Dualism of Massive Particles

The wave-particle dualism was originally thought to be valid for the photon only. A young French physics PhD student, Louis De Broglie had the radical idea that not only the photon, but all particles would exhibit the wave particle dualism, including the electron. Einstein's formula $\lambda = h/mc$ would just need to be slightly rearranged into $\lambda = h/mv$, whereby m would be the mass of the particle, and v would be the velocity of the particle. This idea was much disputed at the time, and Louis De Broglie's PhD thesis was almost not accepted. However, eventually the wave-particle dualism of the electron was proven by electron diffraction experiments, and Louis De Broglie was awarded the Nobel prize in 1929. Today, we believe that all particles show the wave-particle dualism, and no experiment up to this date indicates an exception.

Figure 1.2.5 Louis de Broglie 1892-1987, Nobel Prize 1929 (Attribution: Unknown commons.wikimedia.org/wiki/F...roglie_Big.jpg, PD-US expired)