Photoelectric Effect

When light shines on a material, it is possible under the right circumstances for electrons to be freed or ejected from the surface of a material. From Maxwell's equations one might expect that higher intensities of light would produce a proportionally higher ejection rate of electrons from the surface. But experiment showed this was not to be the case. Philipp Lenard found in an experiment in 1902 that higher intensity light of a particular frequency below a threshold did not lead to ejection of electrons. Rather, only when the frequency was increased beyond a threshold did electrons begin to be ejected, a phenomenon called the *photoelectric effect*. This was an unexpected experimental finding and was explained by Einstein in 1905.

Einstein explained the photoelectric effect by postulating that there must be individual discrete light particles or photons. The photons responsible for ionizing an atom were due to the energy of the individual particles, and not simply the amplitude of the wave. Einstein's discovery in which each photon has an energy $E = h\nu$ revived the earlier corpuscular or particle theory of light in the context of quantization.

A macroscopic light beam is composed of a large number of individual photons each of which is a packet of definite energy $E = h\nu$. The energy that is required for an electron to be liberated from an atom depends on the binding energy of the particular electron and atom. However, for a given atom, such as in a metal, the threshold required in order to see the photoelectric effect can be measured. Light that impinges

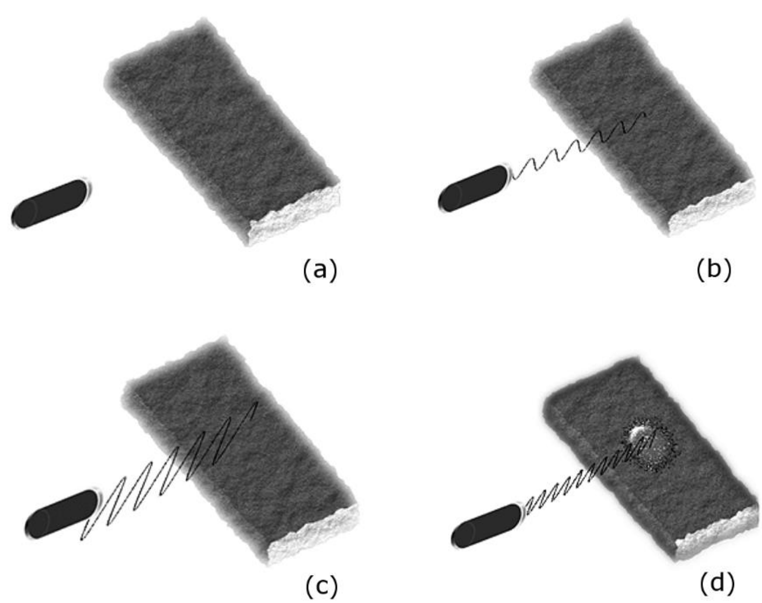

Figure 1.5: (a) Light source and metal (b) low intensity, no electrons ejected (c) high intensity, no electrons ejected (d) high frequency, electrons ejected.

on the photoelectric material with a frequency below this threshold does not lead to appreciable electron ejection; when the frequency of the light is increased beyond this threshold one can measure appreciable electron ejection.

The photoelectric effect is an important discovery in quantum mechanics. It shows that one cannot rely on the wave picture of light alone, but that light possesses an individual particle aspect. To see why this is, suppose that light was a continuum and could be represented as a wave, i.e., not composed of individual particles. Then if light were to interact with matter, it would affect the matter because of its wave-like disturbance. In Figure 1.5(a), a variable frequency and intensity light source is considered that impinges on a metal surface. The case where the frequency of the light source is lower than the binding energy of the electrons in the metal (known as the *Work Function*) is considered in Figure 1.5(b). In this case, no electrons are given off. A given amount of kinetic energy would be expected to be exchanged in such interactions depending on the conditions of the experiment. If one assumes that light is only a single composite wave, then one could expect that by increasing the amplitude of the light wave, the energy exchanged could also be continuously increased further and further until an electron is eventually ejected.

Remarkably however (other than from multiple-photon absorption that is non-linear and typically occurs at a much lower rate), this is not found experimentally when the intensity of the source is increased, as shown in Figure 1.5(c). Only in the case where the frequency of the light is increased beyond the binding energy of the electrons will the process of non-negligible photoionization begin, which is illustrated in Figure 1.5(d). Once non-negligible photoionization does begin, the rate of photoionization can be increased by increasing the intensity of the light source.

The explanation that light is solely a wave, does not appear to be adequate to explain the photoelectric effect. Einstein realized this and proposed that light also has

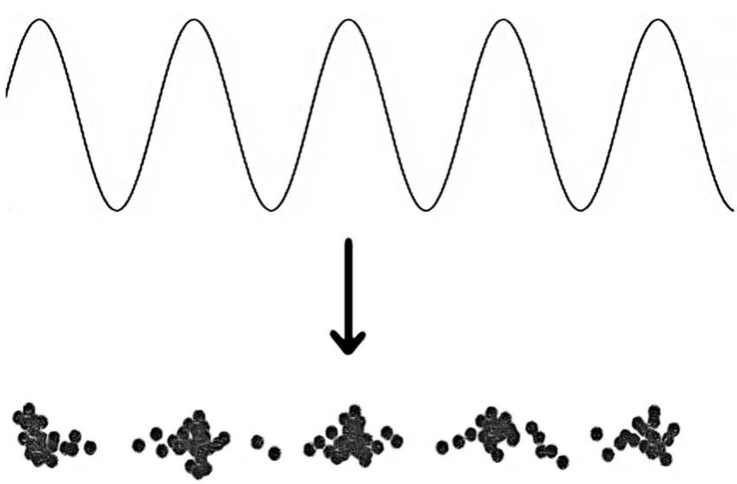

Figure 1.6: Consideration of a wave-particle model of light that is composed of particles that are clustered at the peaks of the wave.

particle properties. One might envision whether or not light could be construed on the basis of a localized particle model. Consider an alternate explanation such that a light wave is composed of small indivisible particle packets as shown in Figure 1.6. In this model, the light particles or individual photons are clustered at the peaks of the wave in a proportional manner, where the occurrence of a photon is related to the squared amplitude of the wave. This wave-particle model (WPM) may at first seem reasonable to explain wave-particle duality.

Assume that each particle packet has an energy $E = h\nu$ where ν is the frequency of the wave. In terms of explaining the photoelectric effect, the model appears to correctly predict electron ejection only when the particles have an energy greater than the threshold of the electron binding energy. Moreover, one can see that if the particles have energy above the electron binding energy then the rate of electron ejection should be proportional to the intensity of the light since there will be more particles, which also agrees with experimental observations. So this model does appear to be reasonable for explaining the photoelectric effect. However, quantum particles were later found to have an additional intrinsic fundamental property called *entanglement* that contradicts this explanation.

Models of this type in which the wave property of light is supplemented by a localized singular particle were considered as early as 1909 by Einstein [3, p. 219]. Einstein contemplated the existence of a vector field surrounding the particles that could extend for large distances. These vector fields from many particles would sum coherently to create forces on other charged particles.