Answer to Essential Question 27.1: (a) Assuming the wavelength is measured in vacuum, we can use the wave equation $f = c / \lambda$ to find that the frequency corresponding to a wavelength of 600 nm is $f = c / \lambda = (3.00 \times 10^8 \text{ m/s}) / (6 \times 10^{-7} \text{ m}) = 5 \times 10^{14}$ Hz. (b) Applying equation 27.1, with $n = 1$, we find that the difference between energy levels is extremely small, being $E = hf = (6.626 \times 10^{-34} \text{ J s}) \times (5 \times 10^{14} \text{ Hz}) = 3 \times 10^{-19}$ J.

27-2 Einstein Explains the Photoelectric Effect

On the previous page, we introduced the photoelectric effect (the emission of electrons from a metal caused by light shining on the metal), and discussed how the wave theory of light led to predictions about the experiment that simply did not fit the experimental observations. It was at this point, in 1905, that Albert Einstein stepped in. First, Einstein built on Planck's explanation of the spectrum of a black body. Planck had theorized that oscillators (such as atoms) in a black body could only take on certain energies, with the energy levels separated by an energy hf, where f is the oscillation frequency. Einstein went on to propose that when such an oscillator dropped from one energy level to the next lowest level, losing an energy hf, the missing energy was given off as light, but given off as a packet of energy. Such packets of energy now go by the name ***photon***. In some sense, then, a photon is like a particle of light, with an energy given by

$$E = hf \text{ ,} \qquad \text{(Equation 27.2: \textbf{Energy of a photon})}$$

where f is the frequency of the electromagnetic wave corresponding to the photon. Note how the wave and particle properties of light are brought together in this equation – the energy of a particle of light depends on the light's frequency.

In applying the photon concept to the photoelectric effect, Einstein modeled the process not as a wave interacting with a metal, but as interactions between single photons and single electrons. If the light incident on the metal has a frequency f, then the beam of light can be thought of as being made up of a stream of photons, each with an energy of hf. If each photon is absorbed by a single electron, giving up its energy to the electron, electrons are emitted from the metal as long as the energy an electron acquires from a photon exceeds the metal's work function, W_0, which represents the minimum binding energy between the electrons and the metal.

Predictions of the particle model of light regarding the photoelectric effect

For the predictions of the wave model, refer to the previous page. The particle model makes quite different predictions for the photoelectric effect than does the wave model, including:

- The frequency corresponding to $hf = W_0$ is a critical frequency (known as the *threshold frequency*) for the experiment. Below this frequency, the energy of the photons is not enough for the electrons to overcome the work function. No electrons are emitted when the frequency of the incident light is less than the threshold frequency. Electrons are emitted only when the frequency of the light exceeds the threshold frequency.
- Treating the process as a single photon – single electron interaction leads to a straightforward equation governing the process that is based on energy conservation. When the frequency of the light exceeds the threshold frequency, part of the photon energy goes into overcoming the binding energy between the electron and the metal, with the energy that remains being carried away by the electron as its kinetic energy. Thus,

$$K_{\max} = hf - W_0 \,. \qquad \text{(Equation 27.3: \textbf{The photoelectric effect})}$$

- Increasing the intensity of the incident light without changing its frequency means that more photons are incident per unit time on a given area. If the light frequency is below the threshold frequency, no electrons are emitted no matter what the intensity is. If the frequency exceeds the threshold frequency, increasing the intensity causes more electrons to be emitted, but the maximum kinetic energy of the emitted electrons does not change.

It took several years for these predictions to be verified; however, by 1915 experiments showed clearly that Einstein was correct, confirming that light has a particle nature. For his explanation of the photoelectric effect, Einstein was awarded the Nobel Prize in Physics in 1921.

EXPLORATION 27.2 – The photoelectric effect experiment

Let's look at one method for carrying out the photoelectric effect experiment. This will involve a review of some of the concepts from Chapter 17, such as electric potential and the workings of a capacitor.

Step 1 – ***A diagram of the experimental apparatus is shown in Figure 27.2. Light of a frequency higher than the work function shines on a metal plate (plate 1), causing electrons to be emitted. These electrons are collected by a second plate (plate 2), and the electrons travel back through a wire from plate 2 to plate 1. An ammeter measures the current in the wire, while an adjustable battery, with a voltage set initially to zero, is also part of the circuit. Explain, using conservation of energy and concepts from Chapter 17, how adjusting the battery voltage enables us to measure the maximum kinetic energy of the emitted electrons. Neglect gravity.***

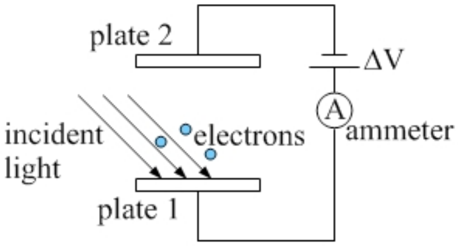

Figure 27.2: A diagram of the experimental apparatus for carrying out the photoelectric effect experiment.

If the battery is connected so plate 2 is negative and plate 1 is positive, electrons emitted from plate 1 do not reach plate 2 unless the kinetic energy they have when they leave plate 1 exceeds the change in electric potential energy, $e\,\Delta V$, associated with electrons crossing the gap from plate 1 to plate 2. The electrons that do not make it across the gap return to plate 1. Thus, as the battery voltage increases from zero, fewer electrons cross the gap and the ammeter reading drops. The smallest battery voltage $\Delta V_{\min}$ needed to bring the current (and the ammeter reading) to zero is directly related to the maximum kinetic energy of the emitted electrons. By energy conservation, the potential energy of the electrons just below plate 2 is equal to the kinetic energy they have at plate 1 (defining plate 1 as the zero for potential energy). In equation form, we have $K_{\max} = e\,\Delta V_{\min}$.

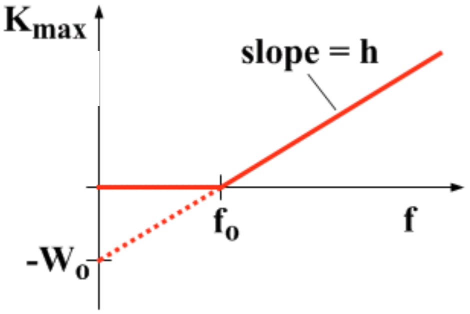

Figure 27.3: A graph of the maximum kinetic energy of electrons emitted when light shines on a metal, as a function of the frequency of the light. Below the threshold frequency, no electrons are emitted. Above the threshold frequency, the maximum kinetic energy of the emitted electrons increases linearly with frequency.

Step 2 – ***Sketch a graph showing the maximum kinetic energy of the electrons as a function of the frequency of the incident light, both above and below the threshold frequency f_0.*** This graph, which matches Equation 27.3, is shown in Figure 27.3.

Key idea: To explain the photoelectric effect experiment, we treat light as being made up of particles called photons. **Related End-of-Chapter Exercises: 4, 5, 42, 46.**

Essential Question 27.2: Plot a graph like that in Figure 27.3, but for a different metal that has a larger threshold frequency. Comment on the similarities and differences between the two graphs.