Chapter 8

Electronic Structure

Opening Essay

Normal light microscopes can magnify objects up to about 1,500 times. Electron microscopes can magnify objects up to 1,000,000 times. Why can electron microscopes magnify images so much?

A microscope's resolution depends on the wavelength of light used. The smaller the wavelength, the more a microscope can magnify. Light is a wave, and, as such, it has a wavelength associated with it. The wavelength of visible light, which is detected by the eyes, varies from about 700 nm to about 400 nm.

One of the startling conclusions about modern science is that electrons also act as waves. However, the wavelength of electrons is much, much shorter—about 0.5 to 1 nm. This allows electron microscopes to magnify 600–700 times more than light microscopes. This allows us to see even smaller features in a world that is invisible to the naked eye.

Atoms act the way they do because of their structure. We already know that atoms are composed of protons, neutrons, and electrons. Protons and neutrons are located in the nucleus, and electrons orbit around the nucleus. But we need to know the structural details to understand why atoms react the way they do.

Virtually everything we know about atoms ultimately comes from light. Before we can understand the composition of atoms (especially electrons), we need to understand the properties of light.
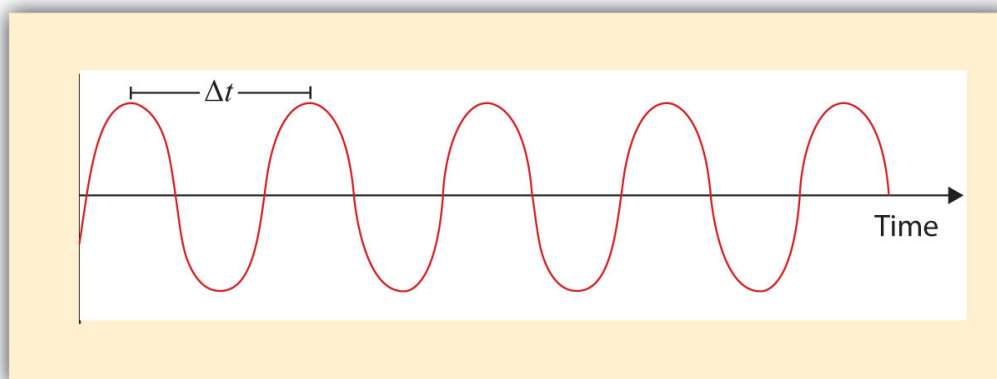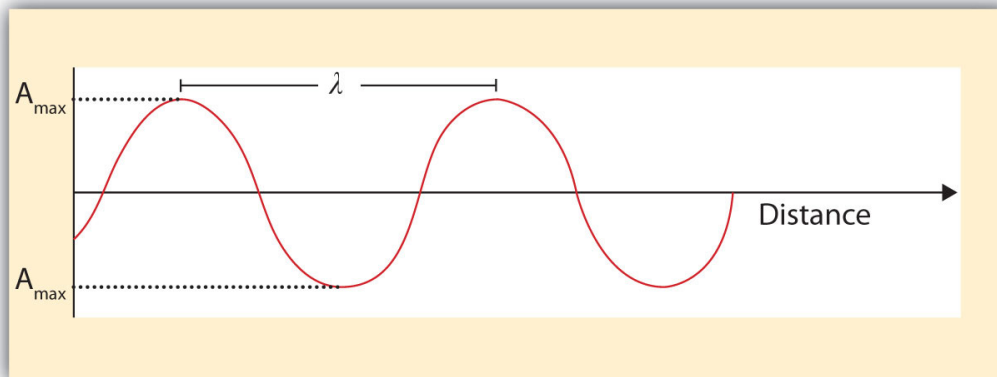
8.1 Light

LEARNING OBJECTIVES

1. Describe light with its frequency and wavelength.
2. Describe light as a particle of energy.

What we know as light is more properly called *electromagnetic radiation*. We know from experiments that light acts as a wave. As such, it can be described as having a frequency and a wavelength. The **wavelength** of light is the distance between corresponding points in two adjacent light cycles, and the **frequency** of light is the number of cycles of light that pass a given point in one second. Wavelength is typically represented by λ, the lowercase Greek letter *lambda*, while frequency is represented by ν, the lowercase Greek letter *nu* (although it looks like a Roman "vee," it is actually the Greek equivalent of the letter "en"). Wavelength has units of length (meters, centimeters, etc.), while frequency has units of *per second*, written as s^{-1} and sometimes called a *hertz* (Hz). Figure 8.1 "Characteristics of Light Waves" shows how these two characteristics are defined.

Figure 8.1 Characteristics of Light Waves

Light acts as a wave and can be described by a wavelength   and a frequency   .
One property of waves is that their speed is equal to their wavelength times their frequency. That means we have

$$\text{speed} = \lambda v$$

For light, however, speed is actually a universal constant when light is traveling through a vacuum (or, to a very good approximation, air). The measured speed of light (c) in a vacuum is 2.9979×10^8 m/s, or about 3.00×10^8 m/s. Thus, we have

$$c = \lambda v$$

Because the speed of light is a constant, the wavelength and the frequency of light are related to each other: as one increases, the other decreases and vice versa. We can use this equation to calculate what one property of light has to be when given the other property.

EXAMPLE 1

What is the frequency of light if its wavelength is 5.55×10^{-7} m?

Solution

We use the equation that relates the wavelength and frequency of light with its speed. We have

$$3.00 \times 10^{8} \text{m/s} = \left(5.55 \times 10^{-7} \text{m}\right)\nu$$

We divide both sides of the equation by 5.55×10^{-7} m and get

$$\nu = 5.41 \times 10^{14} \text{ s}^{-1}$$

Note how the m units cancel, leaving s in the denominator. A unit in a denominator is indicated by a −1 power—s^{-1}—and read as "per second."

Test Yourself

What is the wavelength of light if its frequency is 1.55×10^{10} s^{-1}?

Answer

0.0194 m, or 19.4 mm

Light also behaves like a package of energy. It turns out that for light, the energy of the "package" of energy is proportional to its frequency. (For most waves, energy is proportional to wave amplitude, or the height of the wave.) The mathematical equation that relates the energy (E) of light to its frequency is

$$E=h\nu$$

where ν is the frequency of the light, and h is a constant called **Planck's constant**. Its value is 6.626×10^{-34} J·s—a very small number that is another fundamental constant of our universe, like the speed of light. The units on Planck's constant may look unusual, but these units are required so that the algebra works out.

EXAMPLE 2

What is the energy of light if its frequency is 1.55×10^{10} s^{-1}?

Solution

Using the formula for the energy of light, we have

$E = (6.626 \times 10^{-34}$ J·s$)(1.55 \times 10^{10}$ s$^{-1})$

Seconds are in the numerator and the denominator, so they cancel, leaving us with joules, the unit of energy. So

$E = 1.03 \times 10^{-23}$ J

This is an extremely small amount of energy—but this is for only one light wave.

Test Yourself

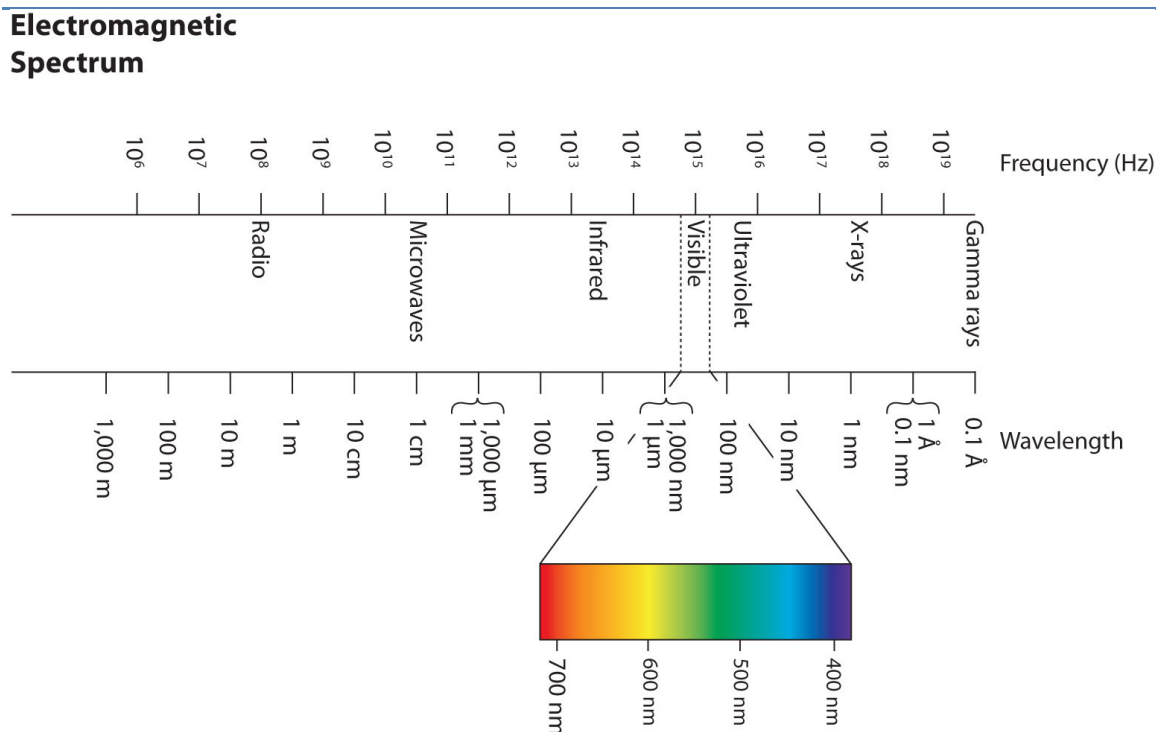What is the frequency of a light wave if its energy is 4.156×10^{-20} J?

Answer
6.27×10^{13} s^{-1}

Because a light wave behaves like a little particle of energy, light waves have a particle-type name: the **photon**. It is not uncommon to hear light described as photons.

Wavelengths, frequencies, and energies of light span a wide range; the entire range of possible values for light is called the **electromagnetic spectrum**. We are mostly familiar with visible light, which is light having a wavelength range between about 400 nm and 700 nm. Light can have much longer and much shorter wavelengths than this, with corresponding variations in frequency and energy. Figure 8.2 "The Electromagnetic Spectrum" shows the entire electromagnetic spectrum and how certain regions of the spectrum are labeled. You may already be familiar with some of these regions; they are all light—with different frequencies, wavelengths, and energies.

Figure 8.2 *The Electromagnetic Spectrum*

The electromagnetic spectrum, with its various regions labeled. The borders of each region are approximate.

KEY TAKEAWAYS

- Light acts like a wave, with a frequency and a wavelength.
- The frequency and wavelength of light are related by the speed of light, a constant.
- Light acts like a particle of energy, whose value is related to the frequency of light.

EXERCISES

1. Describe the characteristics of a light wave.

2. What is a characteristic of a particle of light?

3. What is the frequency of light if its wavelength is 7.33×10^{-5} m?

4. What is the frequency of light if its wavelength is 1.226 m?

5. What is the frequency of light if its wavelength is 733 nm?

6. What is the frequency of light if its wavelength is 8.528 cm?

7. What is the wavelength of light if its frequency is 8.19×10^{14} s^{-1}?

8. What is the wavelength of light if its frequency is 3.66×10^{6} s^{-1}?

9. What is the wavelength of light if its frequency is 1.009×10^{6} Hz?

10. What is the wavelength of light if its frequency is 3.79×10^{-3} Hz?

11. What is the energy of a photon if its frequency is 5.55×10^{13} s^{-1}?

12. What is the energy of a photon if its frequency is 2.06×10^{18} s^{-1}?

13. What is the energy of a photon if its wavelength is 5.88×10^{-4} m?

14. What is the energy of a photon if its wavelength is 1.888×10^{2} m?

ANSWERS

1. Light has a wavelength and a frequency.

3. 4.09×10^{12} s^{-1}

5. 4.09×10^{14} s^{-1}

7. 3.66×10^{-7} m

9. 297 m

11. 3.68×10^{-20} J

13. 3.38×10^{-22} J