

25.7 The Photon Model of Electromagnetic Waves

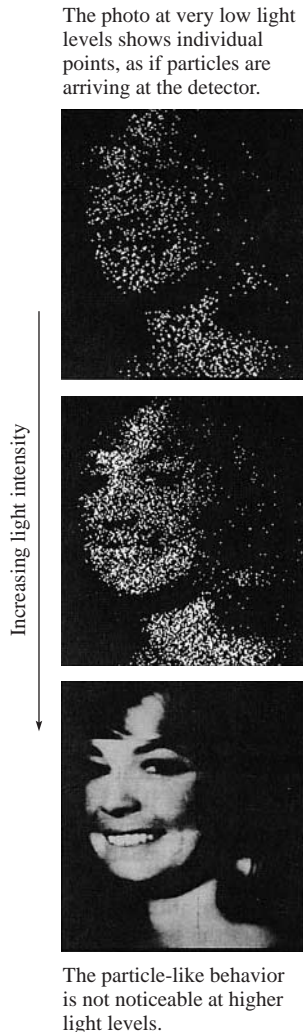


FIGURE 25.33 Photographs made with an increasing level of light intensity.

Figure 25.33 shows three photographs made with a camera in which the film has been replaced by a special high-sensitivity detector. A correct exposure, at the bottom, shows a perfectly normal photograph of a woman. But with very faint illumination (top), the picture is *not* just a dim version of the properly exposed photo. Instead, it is a collection of dots. A few points on the detector have registered the presence of light, but most have not. As the illumination increases, the density of these dots increases until the dots form a full picture.

This is not what we might expect. If light is a wave, reducing its intensity should cause the picture to grow dimmer and dimmer until disappearing, but the entire picture would remain present. It should be like turning down the volume on your stereo until you can no longer hear the sound. Instead, the left photograph in Figure 25.33 looks as if someone randomly threw “pieces” of light at the detector, causing full exposure at some points but no exposure at others.

If we did not know that light is a wave, we would interpret the results of this experiment as evidence that light is a stream of some type of particle-like object. If these particles arrive frequently enough, they overwhelm the detector and it senses a steady “river” instead of the individual particles in the stream. Only at very low intensities do we become aware of the individual particles.

As we will see in Chapter 28, many experiments convincingly lead to the surprising result that **electromagnetic waves, although they are waves, have a particle-like nature.** These particle-like components of electromagnetic waves are called **photons**.

The **photon model** of electromagnetic waves consists of three basic postulates:

1. Electromagnetic waves consist of discrete, massless units called photons. A photon travels in vacuum at the speed of light, 3.00×10^8 m/s.
2. Each photon has energy

$$E_{\text{photon}} = hf \quad (25.20)$$

where f is the frequency of the wave and h is a *universal constant* called **Planck’s constant**. The value of Planck’s constant is

$$h = 6.63 \times 10^{-34} \text{ J} \cdot \text{s}$$

In other words, the electromagnetic waves come in discrete “chunks” of energy hf .

3. The superposition of a sufficiently large number of photons has the characteristics of a continuous electromagnetic wave.

EXAMPLE 25.8 Finding the energy of a photon of visible light

550 nm is the average wavelength of visible light.

- a. What is the energy of a photon with a wavelength of 550 nm?
- b. A 40 W incandescent light bulb emits about 1 J of visible light energy every second. Estimate the number of visible light photons emitted per second.

SOLVE a. The frequency of the photon is

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^8 \text{ m/s}}{550 \times 10^{-9} \text{ m}} = 5.45 \times 10^{14} \text{ Hz}$$

Equation 25.20 gives us the energy of this photon:

$$E_{\text{photon}} = hf = (6.63 \times 10^{-34} \text{ J} \cdot \text{s})(5.45 \times 10^{14} \text{ Hz}) = 3.61 \times 10^{-19} \text{ J}$$

This is an extremely small energy! In fact, photon energies are so small that they are usually measured in electron volts (eV) rather than joules. Recall that $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$. With this, we find that the photon energy is

$$E_{\text{photon}} = 3.61 \times 10^{-19} \text{ J} \times \frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}} = 2.26 \text{ eV}$$

- b. The photons emitted by a light bulb span a range of energies, because the light spans a range of wavelengths, but the *average* photon energy corresponds to a wavelength near 550 nm. Thus we can estimate the number of photons in 1 J of light as

$$N \approx \frac{1 \text{ J}}{3.61 \times 10^{-19} \text{ J/photon}} \approx 3 \times 10^{18} \text{ photons}$$

A typical light bulb emits about 3×10^{18} photons every second.

ASSESS The number of photons emitted per second is staggeringly large. It's not surprising that in our everyday life we would sense only the river and not the individual particles within the flow.

As we saw, a single photon of light at a wavelength of 550 nm has an energy of 2.26 eV. It is worthwhile to see just what 2.26 eV “buys” in interactions with atoms and molecules. Table 25.1 shows some energies required for typical atomic and molecular processes. These values show that 2.26 eV is a significant amount of energy on an atomic scale. It is certainly enough to cause a molecular transformation, and photons with just slightly more energy (shorter wavelength) can break a covalent bond. The photon model of light will be essential as we explore the interaction of electromagnetic waves with matter in coming chapters.

STOP TO THINK 25.5

Two FM radio stations emit radio waves at frequencies of 90.5 MHz and 107.9 MHz. Each station emits the same total power. If you think of the radio waves as photons, which station emits the largest number of photons per second?

- A. The 90.5 MHz station. B. The 107.9 MHz station.
C. Both stations emit the same number of photons per second.

TABLE 25.1 Energies of some atomic and molecular processes

Process	Energy
Breaking a hydrogen bond between two water molecules	0.24 eV
Energy released in metabolizing one molecule of ATP	0.32 eV
Breaking the bond between atoms in a water molecule	4.7 eV
Ionizing a hydrogen atom	13.6 eV

25.8 The Electromagnetic Spectrum

We have now seen two very different ways to look at electromagnetic waves: as oscillating waves of the electric and magnetic field, and as particle-like units of the electromagnetic field called photons. This dual nature of electromagnetic waves is something we will discuss at length in Chapter 28. For now, we will note that each view is appropriate in certain circumstances. For example, we speak of radio *waves* but of x *rays*. The “ray” terminology tells us that x rays are generally better described as photons than as waves.

Figure 25.34 shows the *electromagnetic spectrum* with photon energy (in eV) and wavelength (in m) scales. As you can see, electromagnetic waves span an extraordinarily wide range of wavelengths and energies. Radio waves have wavelengths of many meters but very low photon energies—only a few billionths of an eV. Because the photon energies are so small, radio waves are well described by Maxwell’s theory of electromagnetic waves, as we noted above. At the other end of the spectrum, x rays and gamma rays have very short wavelengths and very high photon energies—large enough to ionize atoms and break molecular bonds. Consequently, x rays and gamma rays, although they do have wave-like characteristics, are best described as photons. Visible light is in the middle. As we will see in Chapter 28, we must consider *both* views to fully understand the nature of visible light.

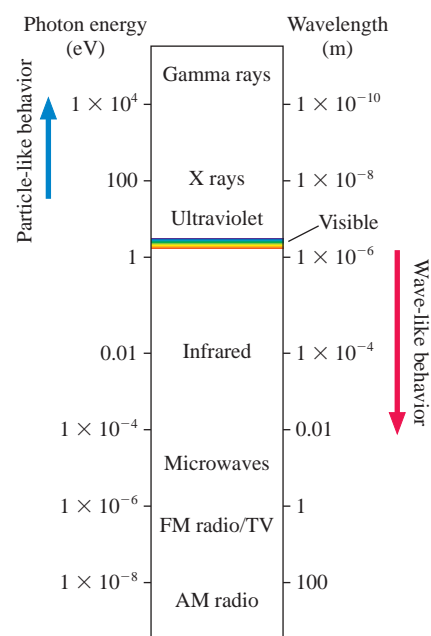


FIGURE 25.34 The electromagnetic spectrum.

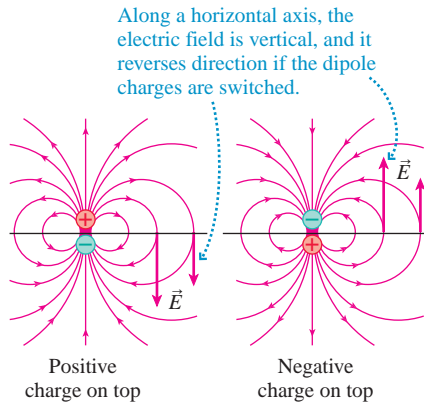


FIGURE 25.35 The electric field of an oscillating dipole.

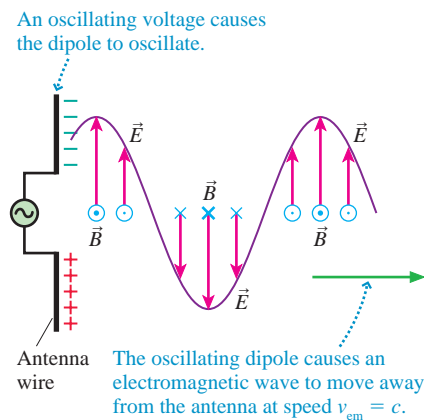
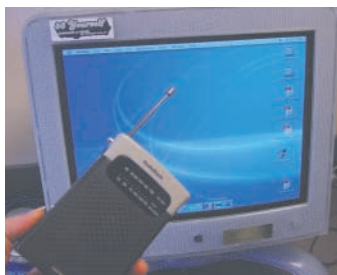


FIGURE 25.36 An antenna generates a self-sustaining electromagnetic wave.

TRY IT YOURSELF



Unwanted transmissions During takeoff and landing, airplane passengers are asked to turn off electronic devices. A simple experiment shows why. Set a radio to the AM band and hold it near a computer. Adjust the radio's tuning while opening a file; you can easily find a radio signal emitted by the hard drive when it is operating, because electromagnetic waves are produced by the rapid switching of electric currents in the drive. All portable electronic devices emit radio waves whether they are designed for communicating or not, and they may cause dangerous interference with airplane systems.

Radio Waves and Microwaves

An electromagnetic wave is self-sustaining, independent of charges or currents. However, charges and currents are needed at the *source* of an electromagnetic wave. Radio waves and microwaves are generally produced by the motion of charged particles in an antenna.

Figure 25.35 reminds you what the electric field of an electric dipole looks like. If the dipole is vertical, the electric field \vec{E} at points along a horizontal line is also vertical. Reversing the dipole, by switching the charges, reverses \vec{E} . If the charges were *oscillate* back and forth, switching position at frequency f , then \vec{E} would oscillate in a vertical plane. The changing \vec{E} would then create an induced magnetic field \vec{B} , which could then create an \vec{E} , which could then create a \vec{B} , . . . and a vertically polarized electromagnetic wave at frequency f would radiate out into space.

This is exactly what an **antenna** does. Figure 25.36 shows two metal wires attached to the terminals of an oscillating voltage source. The figure shows an instant when the top wire is negative and the bottom is positive, but these will reverse in half a cycle. The wire is basically an oscillating dipole, and it creates an oscillating electric field. The oscillating \vec{E} induces an oscillating \vec{B} , and they take off as an electromagnetic wave at speed $v_{em} = c$. The wave does not need oscillating charges as a *wave source*, but once created it is self-sustaining and independent of the source.

Radio waves are *detected* by antennas as well. The electric field of a vertically polarized radio wave drives a current up and down a vertical conductor, producing a potential difference that can be amplified. For best reception, the antenna length should be about $\frac{1}{4}$ of a wavelength. A typical cell phone works at 1.9 GHz, with wavelength $\lambda = c/f = 16$ cm. Thus a cell phone antenna should be about 4 cm long, or about $1\frac{1}{2}$ inches. The antenna on your cell phone may seem quite short, but it is the right length to do its job.

AM radio has a lower frequency and thus a longer wavelength—typically 300 m. Having an antenna that is $\frac{1}{4}$ of a wavelength—75 m long!—is simply not practical. Instead, the antenna in an AM radio consists of a coil of wire wrapped around a core of magnetic material. This antenna detects the *magnetic* field of the radio wave. The changing flux of the wave's magnetic field induces an emf in the coil that is detected and amplified by the receiver.

CONCEPTUAL EXAMPLE 25.1 Orienting a coil antenna

A vertically polarized AM radio wave is traveling to the right. How should you orient a coil antenna to detect the oscillating magnetic field component of the wave?

REASON You want the oscillating magnetic field of the wave to produce the maximum possible induced emf in the coil, which requires the maximum changing flux. The flux is maximum when the coil is perpendicular to the magnetic field of the electromagnetic wave, as in Figure 25.37. Thus the plane of the coil should match the wave's plane of polarization.

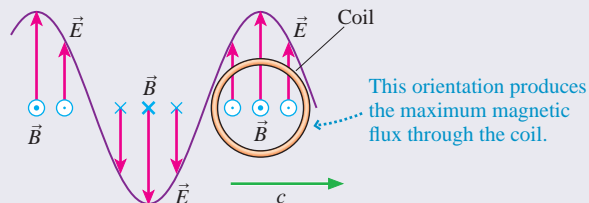
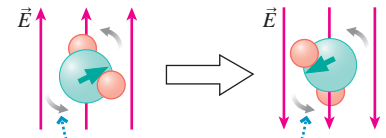


FIGURE 25.37 A coil antenna.

ASSESS Coil antennas are highly directional. If you turn an AM radio—and thus the antenna—in certain directions, you will no longer have the correct orientation of the magnetic field and the coil, and reception will be quite poor.

The electric fields of radio waves and microwaves interact with matter by exerting a torque on molecules, such as water, that have a permanent electric dipole moment, as shown in 25.38. The molecules acquire kinetic energy from the wave, then their collisions with other molecules transform that energy into thermal energy, increasing the temperature.

This is how a microwave oven heats food. A typical home oven uses microwaves of a frequency of 2.45 GHz and a wavelength of 12.2 cm. Water molecules, with their large dipole moment, rotate in response to the electric field of the microwaves, then transfer this energy to the food via molecular collisions. Physical therapists may use electromagnetic waves for deep heating of tissue. The wavelength is generally longer than that in a microwave oven because the longer wavelengths have greater penetration.



The oscillating electric field of the wave rotates the water molecule by exerting an oscillating torque on its electric dipole moment.

FIGURE 25.38 A radio wave interacts with matter.

Infrared, Visible Light, and Ultraviolet

Radio waves can be produced by oscillating charges in an antenna. At the higher frequencies of infrared, visible light, and ultraviolet, the “antennas” are individual atoms. This portion of the electromagnetic spectrum is *atomic radiation*.

Nearly all the atomic radiation in our environment is *thermal radiation* due to the thermal motion of the atoms in an object. As we saw in Chapter 12, thermal radiation—a form of heat transfer—is described by Stefan’s law: If heat energy Q is radiated in a time interval Δt by an object with surface area A and absolute temperature T , the *rate* of heat transfer $Q/\Delta t$ (joules per second) is

$$\frac{Q}{\Delta t} = e\sigma AT^4 \quad (25.21)$$

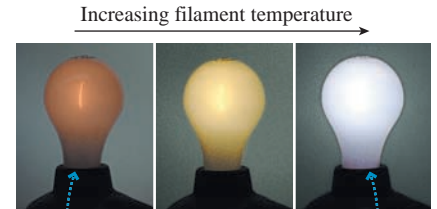
The constant e in this equation is the object’s emissivity, a measure of its effectiveness at emitting electromagnetic waves, and σ is the Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$.

In Chapter 12 we considered the amount of energy radiated and its dependence on temperature. The filament of an incandescent bulb glows simply because it is hot. If you increase the current through a lightbulb, the temperature increases and so does the total energy emitted by the bulb, in accordance with Stefan’s law. The three pictures in Figure 25.39 show a glowing lightbulb with the filament at successively higher temperatures. We can clearly see an increase in brightness in the sequence of three photographs.

But it’s not just the brightness that varies. The *color* of the emitted radiation changes as well. At low temperatures, the light from the bulb is quite red. (A dim bulb doesn’t look this red to your eye because your brain, knowing that the light “should” be white, compensates. But the camera doesn’t lie.) Looking at the change in color as the temperature of the bulb rises in Figure 25.39, we see that **the spectrum of thermal radiation changes with temperature**. It’s this variation in the spectrum that we want to consider in this chapter.

If we measured the intensity of thermal radiation as a function of wavelength for an object at three temperatures, 3500 K, 4500 K, and 5500 K, the data would appear as in Figure 25.40. Notice two important features of the data:

- Increasing the temperature increases the intensity at all wavelengths. **Making the object hotter causes it to emit more radiation across the entire spectrum.**
- Increasing the temperature causes the peak intensity to shift to a shorter wavelength. **The higher the temperature, the shorter the wavelength of the peak of the spectrum.**



At lower filament temperatures, the bulb is dim, and the light is noticeably reddish. When the filament is hotter, the bulb is brighter and the light is whiter.

FIGURE 25.39 The brightness of the bulb varies with the temperature of the filament.

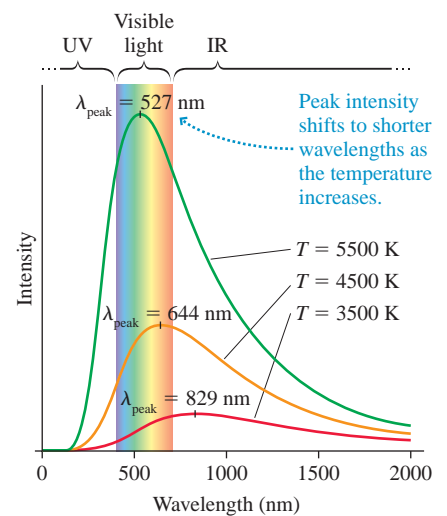


FIGURE 25.40 A thermal emission spectrum depends on the temperature.

The wavelength corresponding to the peak of the intensity graph is given by

$$\lambda_{\text{peak}}(\text{in nm}) = \frac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{T} \quad (25.22)$$

Wien's law for the peak wavelength of a thermal emission spectrum



where the temperature *must* be in kelvin. The spectrum of a hotter object is a taller graph (more energy radiated) with its peak at a shorter wavelength.

EXAMPLE 25.9 Finding peak wavelengths

What are the wavelengths of peak intensity and the corresponding spectral regions for radiating objects at (a) normal human body temperature of 37°C , (b) the temperature of the filament in an incandescent lamp, 1500°C , and (c) the temperature of the surface of the sun, 5800 K ?

PREPARE All of the objects emit thermal radiation.

SOLVE First, we convert temperatures to kelvin. The temperature of the human body is $T = 37 + 273 = 310\text{ K}$ and the filament temperature is $T = 1500 + 273 = 1773\text{ K}$. Equation 25.22 then gives the wavelengths of peak intensity as

$$\text{a. } \lambda_{\text{peak}}(\text{body}) = \frac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{310\text{ K}} = 9.4 \times 10^3 \text{ nm} = 9.4 \mu\text{m}$$

$$\text{b. } \lambda_{\text{peak}}(\text{filament}) = \frac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{1773\text{ K}} = 1600 \text{ nm}$$

$$\text{c. } \lambda_{\text{peak}}(\text{sun}) = \frac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{5800\text{ K}} = 500 \text{ nm}$$

ASSESS The peak of the emission curve at body temperature is far into the infrared region of the spectrum, well below the range of sensitivity of human vision. The sun's emission peaks right in the middle of the visible spectrum, which seems reasonable. Interestingly, most of the energy radiated by an incandescent bulb is *not* visible light. The tail of the emission curve extends into the visible region, but the peak of the emission curve—and most of the emitted energy—is in the infrared region of the spectrum. A 100 W bulb emits only a few watts of visible light.



◀ **It's the pits . . . BIO** Rattlesnakes can hunt in total darkness. Prey animals are warm, and warm objects emit thermal radiation—which the snakes can sense. Rattlesnakes are in a group of snakes known as *pit vipers*. The name comes from a second set of vision organs that are simply pits with sensitive tissue at the bottom. In the photo, the pits appear as dark spots in front of the eyes. The pits are sensitive to infrared wavelengths of $\approx 10\ \mu\text{m}$, near the wavelength of peak emission at mammalian body temperatures. Pit vipers sense the electromagnetic waves *emitted* by warm-blooded animals. They need no light to “see” you. You emit a “glow” they can detect.

Infrared radiation, with its relatively long wavelength and low photon energy, produces effects in tissue similar to those of microwaves—heating—but the penetration is much less than for microwaves. Infrared is absorbed mostly by the top layer of your skin and simply warms you up, as you know from sitting in the sun or under a heat lamp. The wave picture is generally most appropriate for infrared.

In contrast, ultraviolet photons have enough energy to interact with molecules in entirely different ways, ionizing molecules and breaking molecular bonds. The cells in skin are altered by ultraviolet radiation, causing sun tanning and sun burning. DNA molecules can be permanently damaged by ultraviolet radiation. There is a reasonably sharp threshold for such damage at 290 nm (corresponding to 4.3 eV photon energy). At longer wavelengths, damage to cells is slight; at shorter wavelengths, it is extensive. Ultraviolet lamps are very effective at sterilizing surfaces because they disrupt the genetic material of bacteria sufficiently to kill them. These interactions of ultraviolet radiation with matter are best understood from the photon perspective, with the absorption of each photon being associated with a particular molecular event.

Visible light is at a transition point in the electromagnetic spectrum. Your studies of wave optics in Chapter 17 showed you that light has a wave nature. At the same time, the energy of photons of visible light is large enough to cause molecular transitions—which is how your eye detects light. The bending of light by the lens of the eye requires us to think of light as a wave, but the detection of light

by the cells in the retina requires us to think of light as photons. When we work with visible light, we will often move back and forth between the wave and photon models.

EXAMPLE 25.10 Finding the photon energy for ultraviolet light

Ultraviolet radiation with a wavelength of 254 nm is used in germicidal lamps. What is the photon energy in eV for such a lamp?

SOLVE The photon energy is $E = hf$:

$$E = hf = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34} \text{ J} \cdot \text{s})(3.00 \times 10^8 \text{ m/s})}{254 \times 10^{-9} \text{ m}}$$

$$= 7.83 \times 10^{-19} \text{ J}$$

In eV, this is

$$E = 7.83 \times 10^{-19} \text{ J} \times \frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}} = 4.89 \text{ eV}$$

ASSESS Table 25.1 shows that this energy is sufficient to break the bonds in a water molecule. It will be enough energy to break other bonds as well, leading to damage on a cellular level.

Color Vision

The cones, the color-sensitive cells in the retina of the eye, each contain one of three slightly different forms of a light-sensitive photopigment. A single photon of light can trigger a reaction in a photopigment molecule, which ultimately leads to a signal being produced by a cell in the retina. The energy of the photon must be matched to the energy of a molecular transition for absorption of the photon energy to take place. Each photopigment has a range of photon energies to which it is sensitive. Our color vision is a result of the differential response of the three types of cones containing these three different pigments, shown in Figure 25.41.

CONCEPTUAL EXAMPLE 25.2 Creating the impression of a color

Computer monitors and color TVs can create millions of different colors by combining light from pixels of only three colors: red, green, and blue. These are called RGB displays. How do they do it?

REASON We've seen that there are three different types of cones in the eye. By using differing amounts of three pure colors, we can independently stimulate each of the cone types and thus mimic the response of the eye to light of almost any color.

ASSESS The fact that there are three primary colors of light—red, green, and blue—is a function of our physiology, not basic physics.

Humans have three color photopigments, mice have two, and chickens four—giving them keener color vision than you. The three color photopigments that bees possess give them excellent color vision, but a bee's color sense is different from a human's. The peak sensitivities of a bee's photopigments are in the yellow, blue, and ultraviolet regions of the spectrum. A bee can't see the red of a rose, but it is quite sensitive to ultraviolet wavelengths well beyond the range of human vision. The flowers in the photo at the start of the chapter look pretty to us, but their coloration is really intended for other eyes. The ring of ultraviolet-absorbing pigments near the center of the flower, which is invisible to humans, helps bees zero in on the pollen.

X Rays and Gamma Rays

At the highest energies of the electromagnetic spectrum we find x rays and gamma rays. There is no sharp dividing line between these two regions of the spectrum; the difference is the source of radiation. High-energy photons emitted by electrons are called x rays. If the source is a nuclear process, we call them gamma rays.

We will look at the emission of x rays in atomic processes and gamma rays in nuclear processes in Part VII. For now, we will focus on the “artificial” production of x rays in an x-ray tube, such as the one shown in Figure 25.42.

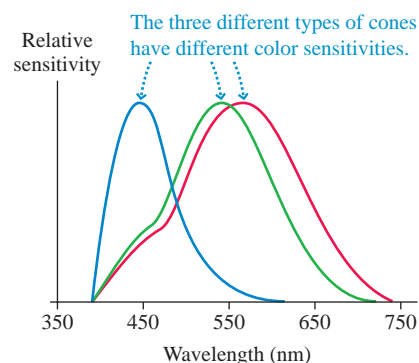


FIGURE 25.41 The sensitivity of different cones in the human eye.

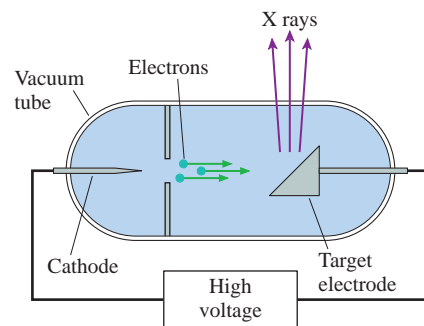


FIGURE 25.42 A simple x-ray tube.

Electrons are emitted from a cathode and accelerated to a kinetic energy of several thousand eV by the electric field between two electrodes connected to a high-voltage power supply. The electrons make a sudden stop when they hit a metal target electrode. The rapid deceleration of an electron can cause the emission of a single photon with a significant fraction of the electron's kinetic energy. These photons, with energies well in excess of 1000 eV, are x rays. The x rays pass through a window in the tube and then may be used to produce an image or to treat a disease.

EXAMPLE 25.11 Determining x-ray energies

An x-ray tube used for medical work has an accelerating voltage of 30 kV. What is the maximum energy of an x-ray photon that can be produced in this tube? What is the wavelength of this x ray?

SOLVE An electron accelerated through a potential difference of 30 kV acquires a kinetic energy of 30 keV. When this electron hits the metal target and stops, energy may be converted to an x ray. The maximum energy that could be converted is 30 keV, so this is the maximum possible energy of an x-ray photon from the tube. In joules, this energy is

$$E = 30 \times 10^3 \text{ eV} \times \frac{1.60 \times 10^{-19} \text{ J}}{1 \text{ eV}} = 4.8 \times 10^{-15} \text{ J}$$

For electromagnetic waves, $c = f\lambda$, so we can calculate

$$\begin{aligned} \lambda &= \frac{c}{f} = \frac{c}{E/h} = \frac{hc}{E} = \frac{(6.63 \times 10^{-34} \text{ J} \cdot \text{s})(3.00 \times 10^8 \text{ m/s})}{4.8 \times 10^{-15} \text{ J}} \\ &= 4.1 \times 10^{-11} \text{ m} = 0.041 \text{ nm} \end{aligned}$$

ASSESS This is a very short wavelength, comparable to the spacing between atoms in a solid.

X rays and gamma rays (and the short-wavelength part of the ultraviolet spectrum) are **ionizing radiation**; the individual photons have sufficient energy to ionize atoms. When such radiation strikes tissue, the resulting ionization can produce cellular damage. When people speak of “radiation” they often mean “ionizing radiation.” Ionizing radiation can be harmful to cells, but, as we will see in Chapter 30, it can also be put to good use in radiation therapy to treat cancer. Rapidly dividing cells—such as those in a tumor—are especially sensitive to the damage from ionizing radiation.

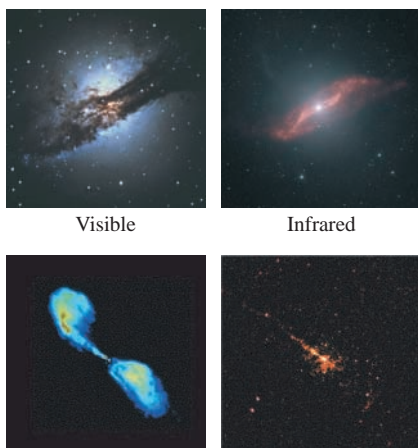
X rays and gamma rays are very penetrating, but the absorption of these high-energy photons is greater in materials made of atoms with more electrons. This is why x rays are used in medical and dental imaging. The calcium in bones has many more electrons and thus is much more absorbing than the hydrogen, carbon, and oxygen that make up most of our soft tissue, so we can use x rays to image bones and teeth.

At several points in this chapter we have hinted at places where a full understanding of the phenomena requires some new physics. We have used the photon model of electromagnetic waves, and we have mentioned that nuclear processes can give rise to gamma rays. There are other questions that we did not raise, such as why the electromagnetic spectrum of a hot object has the shape that it does. These puzzles began to arise in the late 1800s and early 1900s, and it soon became clear that the physics of Newton and Maxwell was not sufficient to fully describe the nature of matter and energy. Some new rules, some new models, were needed. After the next chapter, in which we look at AC circuits, we will return to these puzzles as we begin to explore the exciting notions of quantum physics in Part VII.

STOP TO THINK 25.6

A group of four stars, all the same size, have the four different surface temperatures given below. What is the temperature of the star that emits the most red light?

- A. 3000 K B. 4000 K C. 5000 K D. 6000 K



Seeing the universe in a different light

These four images of the Centaurus A galaxy have the same magnification and orientation, but they are records of different types of electromagnetic waves. (All but the visible light image are false-color images.) The visible light image shows a dark dust lane cutting across the galaxy. In the infrared, this dust lane glows quite brightly—telling us that the dust particles are hot. The radio and x ray images show jets of matter streaming out of the galaxy's center, hinting at the presence of a massive black hole. Views of the cosmos beyond the visible range are important tools of modern astronomy.