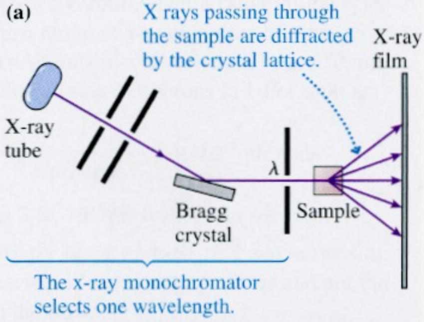
Although the Bragg procedure is straightforward, practical x-ray diffraction looks at the diffraction of x rays that are *transmitted* through a crystal. **FIGURE 25.8a** shows a typical experiment. An x-ray tube generates several x-ray wavelengths, so Bragg diffraction is first used to select just one of these wavelengths by rotating a crystal to an angle meeting the Bragg condition. This part of the apparatus is called an *x-ray monochromator,* a device that selects one (mono) wavelength.

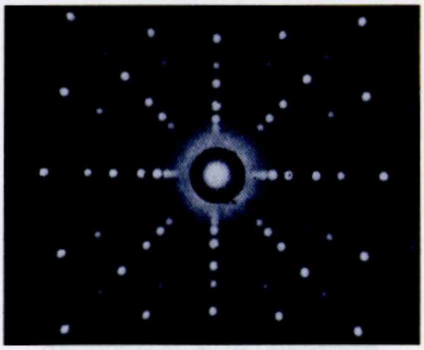
The known wavelength then passes through the sample and is diffracted by the three-dimensional grating of the crystal lattice. An x-ray film behind the sample records the locations of constructive interference. Because the grating is three-dimensional, the diffraction pattern consists of bright points rather than lines or fringes. **FIGURE 25.8b** shows a typical diffraction pattern. You can see that it is quite complicated. Nonetheless, crystallographers have developed many powerful analysis tools for deciphering such patterns. These techniques are computationally very intense, but modern supercomputers have made such analyses routine.

Today, x-ray diffraction is an essential tool for studying the atomic and molecular structure of solids. The most important properties of solids—their strength, chemical properties, ability to be cut or welded, optical properties, and so on—are consequences of their crystal structure. Modern engineering could not exist without the knowledge of materials gained through x-ray diffraction. Similarly, x-ray diffraction was used to deduce the double-helix structure of DNA, and it continues to elucidate the structures of biological molecules such as proteins. The techniques of x-ray diffraction are likely to become even more important in the future as physicists develop new superconducting materials, molecular biologists produce "designer drugs," and engineers design atomic-size nanostructures.

FIGURE 25.8 Using x-ray diffraction to study the atomic structure of a sample.



(b) X-ray diffraction pattern for niobium diboride

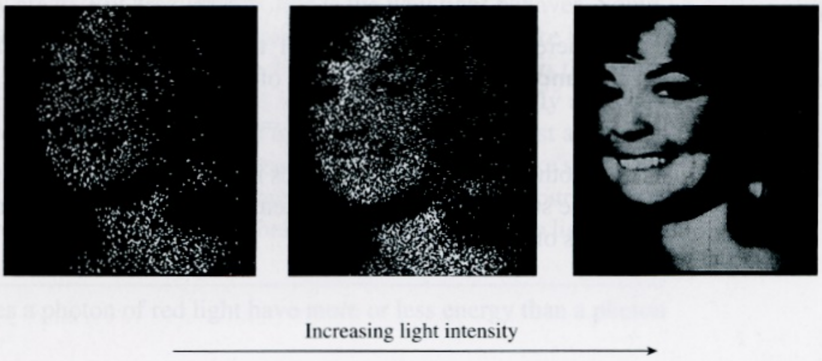


STOP TO THINK 25.1 The first-order diffraction of monochromatic x rays from crystal A occurs at an angle of 20°. The first-order diffraction of the same x rays from crystal B occurs at 30°. Which crystal has the larger atomic spacing?

25.3 Photons

FIGURE 25.9 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 right, shows a perfectly normal photograph of a woman. But with very faint illumination (left), 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.

FIGURE 25.9 Photographs made with increasing levels of light intensity.



The photo at very low light levels shows individual points, as if particles are arriving at the detector.

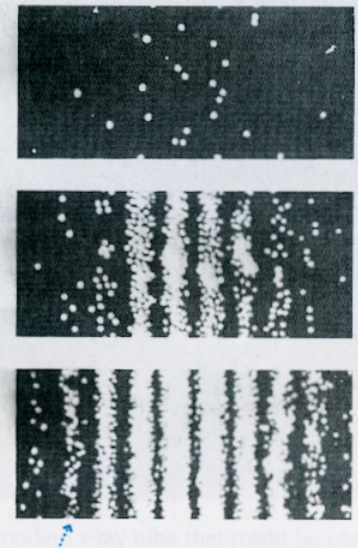
The particle-like behavior is not noticeable at higher light levels.

This is not what we expected. If light is a wave, reducing its intensity should cause the picture to grow dimmer and dimmer until it disappears, 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 25.9 looks as if someone randomly threw "pieces" of light at the detector, causing full exposure at a few *discrete* 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.

Double-Slit Interference Revisited

FIGURE 25.10 A simulation of a double-slit interference experiment with very low but increasing levels of light.


The particle-like dots arrange themselves into wave-like interference fringes.

The particle-like behavior of light seen in Figure 25.9 was apparent only for very low-intensity light. Let's return to the experiment that showed most dramatically the wave nature of light—Young's double-slit interference experiment—and lower the light intensity by inserting filters between the light source and the slits. We cannot expect to see the interference fringes by eye for such a low intensity, so we will replace the viewing screen with the same detector used to make the photographs of Figure 25.9.

What would we predict for the outcome of this experiment? If light is a wave, there is no reason to think that the nature of the interference fringes will change. The detector should continue to show alternating light and dark bands that become dimmer and dimmer until they vanish.

FIGURE 25.10 shows the outcome of such an experiment at three low but increasing light levels. Contrary to our prediction, the detector shows bright dots like those seen in Figure 25.9. The detector is registering particle-like objects. They arrive one by one, and each is localized at a specific point on the detector. This is particle-like behavior, not wave-like behavior. (Waves, you will recall, are not localized at a specific point in space.) But these dots of light are not entirely random. They are grouped into bands at *exactly* the positions where we expected to see bright constructive interference fringes.

The Photon Model of Light

Figures 25.9 and 25.10 are our first evidence of the particle-like nature of light. These particle-like components of light are called **photons.** The concept of the photon was introduced by Albert Einstein to explain an experiment called the photoelectric effect, an experiment we will investigate in Part VII.

The **photon model** of light consists of three basic postulates:

1. Light consists 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

   $$E_{\text{photon}} = hf \tag{25.4}$$

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

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

   In other words, the light comes in discrete "chunks" of energy hf.
3. The superposition of a sufficiently large number of photons has the characteristics of a classical light wave.

EXAMPLE 25.2 The energy of a photon

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 typical incandescent lightbulb emits about 1 J of visible light energy every second. Estimate the number of photons emitted per second.

SOLVE a. The frequency of the photon is

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}\ \text{m/s}}{550 \times 10^{-9}\ \text{m}} = 5.4 \times 10^{14}\ \text{Hz}$$

Equation 25.4 gives us the energy of this photon:

$$E_{\text{photon}} = hf = (6.63 \times 10^{-34}\ \text{J s})(5.4 \times 10^{14}\ \text{Hz})$$
$$= 3.6 \times 10^{-19}\ \text{J}$$

This is an extremely small energy!

b. The photons emitted by a lightbulb 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

$$N \approx \frac{1\ \text{J}}{3.6 \times 10^{-19}\ \text{J/photon}} \approx 3 \times 10^{18}\ \text{photons}$$

A lightbulb emits about 3×10^{18} photons every second.

ASSESS This is a staggeringly large number. It's not surprising that in our everyday life we would sense only the river and not the individual particles within the flow.

Most light sources with which you are familiar emit such vast numbers of photons that you are aware of only their wave-like superposition, just as you notice only the roar of a heavy rain on your roof and not the individual raindrops. But at extremely low intensities the light begins to appear as a stream of individual photons, like the random patter of raindrops when it is barely sprinkling. Each dot on the detector in Figures 25.9 and 25.10 signifies a point where one individual photon delivered its energy and caused a measurable signal.

Although photons are particle like, they are certainly not classical particles. Classical particles, such as Newton's corpuscles of light, would travel in straight lines through the two slits of a double-slit experiment and make just two bright areas on the detector. Instead, as Figure 25.10 shows, the *particle*-like photons seem to be landing at places where a *wave* undergoes constructive interference, thus forming the bands of dots.

Suppose that the detector in the double-slit interference experiment is 30 cm behind the slits and that the light intensity is so low that only 10^6 photons arrive per second. This is experimentally quite feasible. On average, a new photon passes through the slits every 10^{-6} s. A photon moving at the speed of light travels distance $d = c\Delta t = 300$ m during 10^{-6} s. While one photon is traveling the 30 cm between the slits and the detector, the next photon is 300 m away. Or in the likely case that the light source is closer to the slits than 300 m, the next photon has not yet even been emitted by the light source! Under these conditions, only one photon at a time is passing through the double-slit apparatus.

If particle-like photons arrive at the detector in a banded pattern as a consequence of wave-like interference, but if only one photon at a time is passing through the experiment, what is it interfering with? The only possible answer is that the photon is somehow interfering *with itself.* Nothing else is present. But if each photon interferes with itself, rather than with other photons, then each photon, despite the fact that it is a particle-like object, must somehow go through *both* slits!

This all seems pretty crazy. But crazy or not, this is the way light behaves. Sometimes it exhibits particle-like behavior and sometimes it exhibits wave-like behavior. You may be expecting that we will now bring forth an "explanation" so that these observations will all "make sense." Sorry. This is simply how light really and truly behaves. The thing we call *light* is stranger and more complex than it first appeared, and there just is no way for these seemingly contradictory behaviors to make sense. We have to accept nature as it is rather than hoping that nature will conform to our expectations. Furthermore, this half-wave/half-particle behavior is not restricted to light.

STOP TO THINK 25.2 Does a photon of red light have more or less energy than a photon of blue light?