EXERCISE D When a photon scatters off an electron by the Compton effect, which of the following increase: its energy, frequency, wavelength?

EXAMPLE 27–8 **X-ray scattering.** X-rays of wavelength 0.140 nm are scattered from a very thin slice of carbon. What will be the wavelengths of X-rays scattered at (*a*) 0°, (*b*) 90°, (*c*) 180°?

APPROACH This is an example of the Compton effect, and we use Eq. 27–7 to find the wavelengths.

SOLUTION (*a*) For $\phi = 0°, \cos\phi = 1$ and $1 - \cos\phi = 0$. Then Eq. 27–7 gives $\lambda' = \lambda = 0.140\text{ nm}$. This makes sense since for $\phi = 0°$, there really isn't any collision as the photon goes straight through without interacting.
(*b*) For $\phi = 90°, \cos\phi = 0$, and $1 - \cos\phi = 1$. So

$$\lambda' = \lambda + \frac{h}{m_0c} = 0.140\text{ nm} + \frac{6.63 \times 10^{-34}\text{ J}\cdot\text{s}}{(9.11 \times 10^{-31}\text{ kg})(3.00 \times 10^8\text{ m/s})}$$
$$= 0.140\text{ nm} + 2.4 \times 10^{-12}\text{ m} = 0.142\text{ nm};$$

that is, the wavelength is longer by one Compton wavelength (= 0.0024 nm for an electron).
(*c*) For $\phi = 180°$, which means the photon is scattered backward, returning in the direction from which it came (a direct "head-on" collision), $\cos\phi = -1$, and $1 - \cos\phi = 2$. So

$$\lambda' = \lambda + 2\frac{h}{m_0c} = 0.140\text{ nm} + 2(0.0024\text{ nm}) = 0.145\text{ nm}.$$

NOTE The maximum shift in wavelength occurs for backward scattering, and it is twice the Compton wavelength.

PHYSICS APPLIED
Measuring bone density

The Compton effect has been used to diagnose bone disease such as osteoporosis. Gamma rays, which are photons of even shorter wavelength than X-rays, coming from a radioactive source are scattered off bone material. The total intensity of the scattered radiation is proportional to the density of electrons, which is in turn proportional to the bone density. Changes in the density of bone can indicate the onset of osteoporosis.

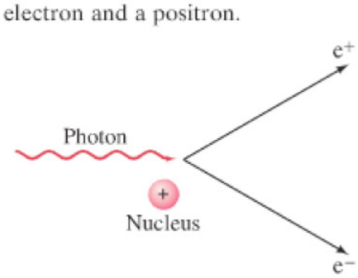
27–6 Photon Interactions; Pair Production

When a photon passes through matter, it interacts with the atoms and electrons. There are four important types of interactions that a photon can undergo:

Photon interactions

1. The *photoelectric effect*: a photon may knock an electron out of an atom and in the process itself disappear.
2. The photon may knock an atomic electron to a higher energy state in the atom if its energy is not sufficient to knock the electron out altogether. In this process the photon also disappears, and all its energy is given to the atom. Such an atom is then said to be in an *excited state*, and we shall discuss it more later.
3. The photon can be scattered from an electron (or a nucleus) and in the process lose some energy; this is the *Compton effect* (Section 27–5). But notice that the photon is not slowed down. It still travels with speed c, but its frequency will be lower because it has lost some energy.
4. *Pair production*: A photon can actually create matter, such as the production of an electron and a positron, Fig. 27–10. (A positron has the same mass as an electron, but the opposite charge, $+e$.)

FIGURE 27–10 Pair production: a photon disappears and produces an electron and a positron.



In process 4, **pair production**, the photon disappears in the process of creating the electron–positron pair. This is an example of rest mass being created from pure energy, and it occurs in accord with Einstein's equation $E = mc^2$.