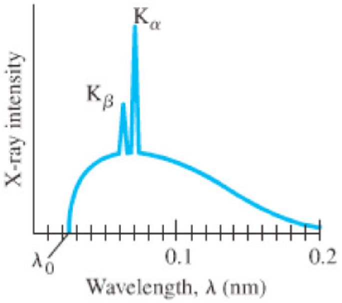
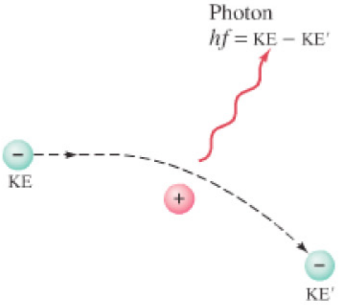


**FIGURE 28–11** (repeated) Spectrum of X-rays emitted from a molybdenum target in an X-ray tube operated at 50 kV.

**FIGURE 28–13** Bremsstrahlung photon produced by an electron decelerated by interaction with a target atom.



Now we briefly analyze the continuous part of an X-ray spectrum (Fig. 28–11) based on the photon theory of light. When electrons strike the target, they collide with atoms of the material and give up most of their energy as heat (about 99%, so X-ray tubes must be cooled). Electrons can also give up energy by emitting a photon of light: an electron decelerated by interaction with atoms of the target (Fig. 28–13) emits radiation because of its deceleration (Chapter 22), and in this case it is called **bremsstrahlung** (German for "braking radiation"). Because energy is conserved, the energy of the emitted photon, $hf$, must equal the loss of kinetic energy of the electron, $\Delta\text{KE} = \text{KE} - \text{KE}'$, so

$$hf = \Delta\text{KE}.$$

An electron may lose all or a part of its energy in such a collision. The continuous X-ray spectrum (Fig. 28–11) is explained as being due to such bremsstrahlung collisions in which varying amounts of energy are lost by the electrons. The shortest-wavelength X-ray (the highest frequency) must be due to an electron that gives up *all* its kinetic energy to produce one photon in a single collision. Since the initial kinetic energy of an electron is equal to the energy given it by the accelerating voltage, $V$, then $\text{KE} = eV$. In a single collision in which the electron is brought to rest ($\text{KE}' = 0$), then $\Delta\text{KE} = eV$ and

$$hf_0 = eV.$$

We set $f_0 = c/\lambda_0$ where $\lambda_0$ is the cutoff wavelength (Fig. 28–11) and find

$$\lambda_0 = \frac{hc}{eV}. \tag{28–4}$$

This prediction for $\lambda_0$ corresponds precisely with that observed experimentally. This result is further evidence that X-rays are a form of electromagnetic radiation (light) and that the photon theory of light is valid.

**EXAMPLE 28–8** **Cutoff wavelength.** What is the shortest-wavelength X-ray photon emitted in an X-ray tube subjected to 50 kV?

**APPROACH** The electrons striking the target will have a KE of 50 keV. The shortest-wavelength photons are due to collisions in which all of the electron's KE is given to the photon so $\text{KE} = eV = hf_0$.

**SOLUTION** From Eq. 28–4,

$$\lambda_0 = \frac{hc}{eV} = \frac{(6.63 \times 10^{-34}\,\text{J}\cdot\text{s})(3.0 \times 10^8\,\text{m/s})}{(1.6 \times 10^{-19}\,\text{C})(5.0 \times 10^4\,\text{V})} = 2.5 \times 10^{-11}\,\text{m},$$

or 0.025 nm.

**NOTE** This result agrees well with experiment, Fig. 28–11.

## * 28–10 Fluorescence and Phosphorescence

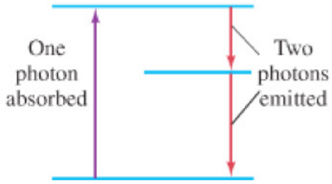


**FIGURE 28–14** Fluorescence.

**PHYSICS APPLIED**
*Fluorescence analysis and fluorescent lightbulbs*

When an atom is excited from one energy state to a higher one by the absorption of a photon, it may return to the lower level in a series of two (or more) jumps if there is an energy level in between (Fig. 28–14). The photons emitted will consequently have lower energy and frequency than the absorbed photon. When the absorbed photon is in the UV and the emitted photons are in the visible region of the spectrum, this phenomenon is called **fluorescence** (Fig. 28–15).

The wavelength for which fluorescence will occur depends on the energy levels of the particular atoms. Because the frequencies are different for different