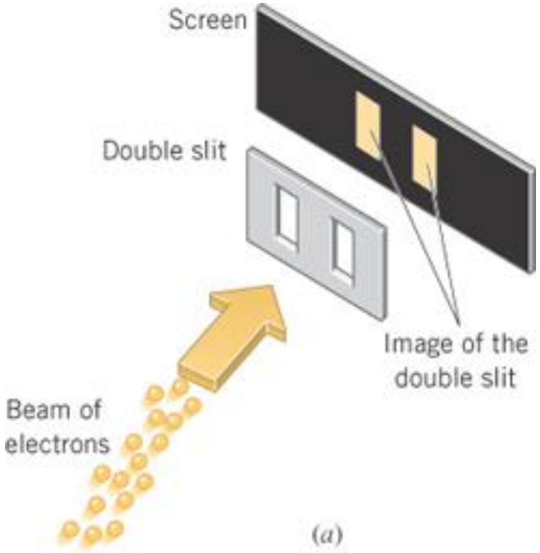
Chapter 29

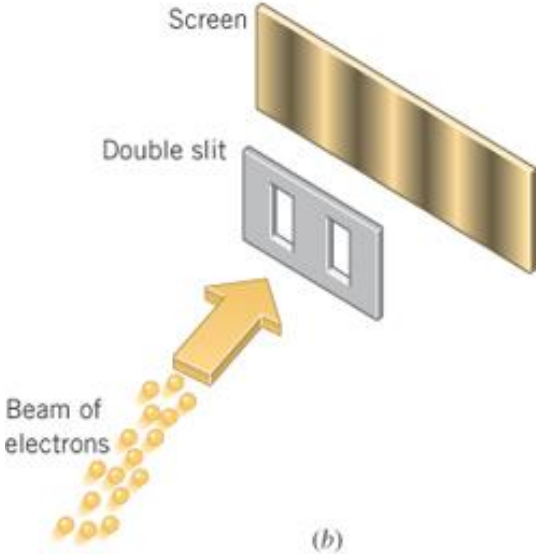
Particles and Waves

29.1 Wave Particle Duality



(a)

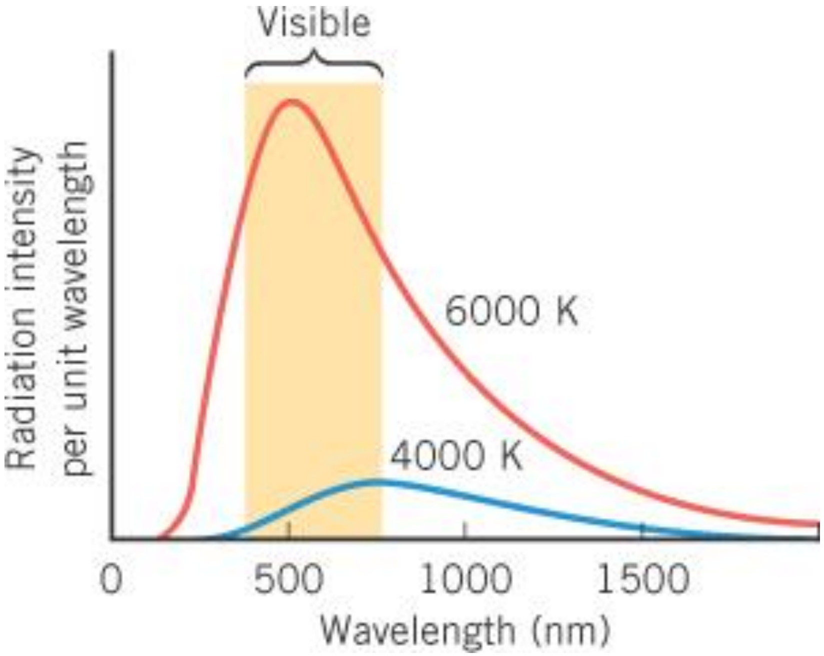
When a beam of electrons is used in a Young's double slit experiment, a fringe pattern occurs, indicating interference effects.



(b)

Waves can exhibit particle-like characteristics, and particles can exhibit wave-like characteristics.

29.2 Blackbody Radiation and Planck's Constant



All bodies, no matter how hot or cold, continuously radiate electromagnetic waves.

Electromagnetic energy is quantized.

frequency

$$E = nhf \qquad n = 0, 1, 2, 3, \ldots$$

Planck's constant

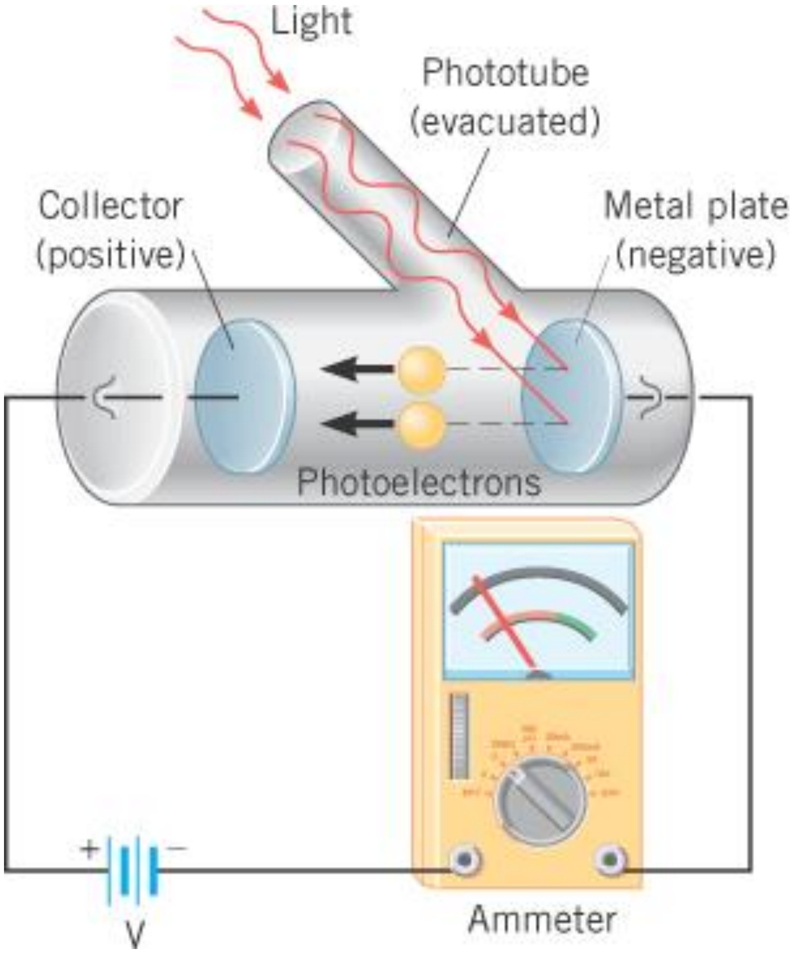
$$h = 6.626 \times 10^{-34}\,\mathrm{J \cdot s}$$

29.3 Photons and the Photoelectric Effect

Electromagnetic waves are composed of particle-like entities called ***photons.***

$$E = hf \qquad\qquad p = h/\lambda$$

29.3 Photons and the Photoelectric Effect



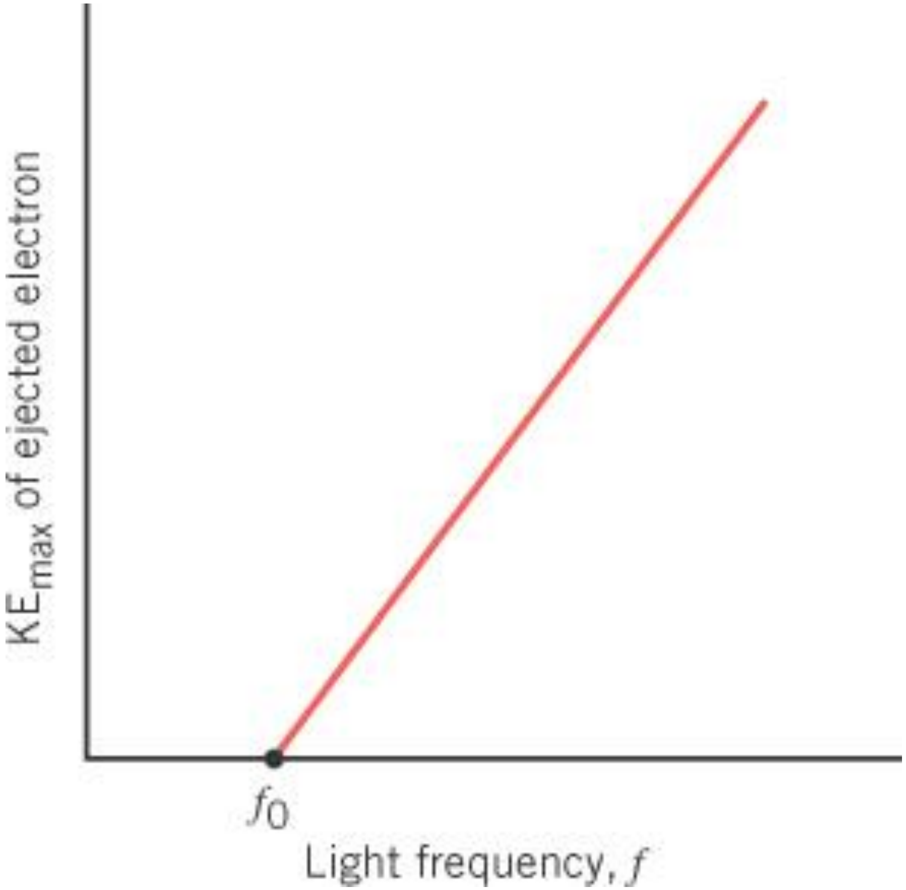
Experimental evidence that light consists of photons comes from a phenomenon called the ***photoelectric effect.***

29.3 Photons and the Photoelectric Effect

When light shines on a metal, a photon can give up its energy to an electron in that metal. The minimum energy required to remove the least strongly held electrons is called the ***work function.***

$$\underbrace{hf}_{\substack{\text{Photon}\\ \text{energy}}} = \underbrace{\mathrm{KE}_{\max}}_{\substack{\text{Maximum}\\ \text{kinetic energy}\\ \text{of ejected electron}}} + \underbrace{W_o}_{\substack{\text{Minimum}\\ \text{work needed to}\\ \text{eject electron}}}$$

29.3 Photons and the Photoelectric Effect



$$\underbrace{\mathrm{KE}_{\mathrm{max}}}_{\substack{\text{Maximum} \\ \text{kinetic energy} \\ \text{of ejected electron}}} = \underbrace{hf}_{\substack{\text{Photon} \\ \text{energy}}} - \underbrace{W_o}_{\substack{\text{Minimum} \\ \text{work needed to} \\ \text{eject electron}}}$$

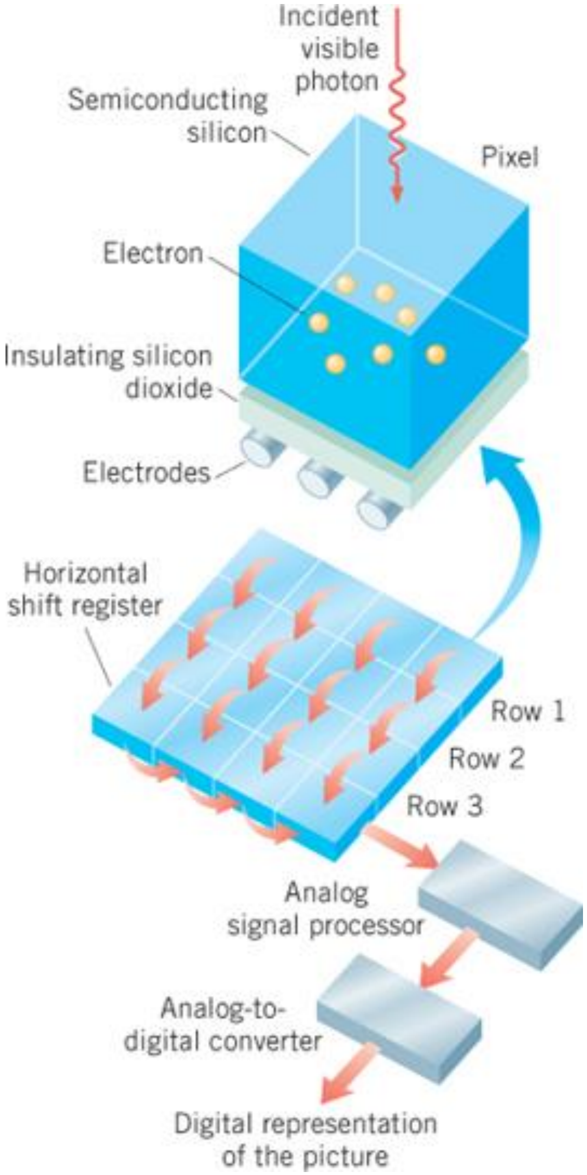
Example 2 The Photoelectric Effect for a Silver Surface

The work function for a silver surface is 4.73 eV. Find the minimum frequency that light must have to eject electrons from the surface.

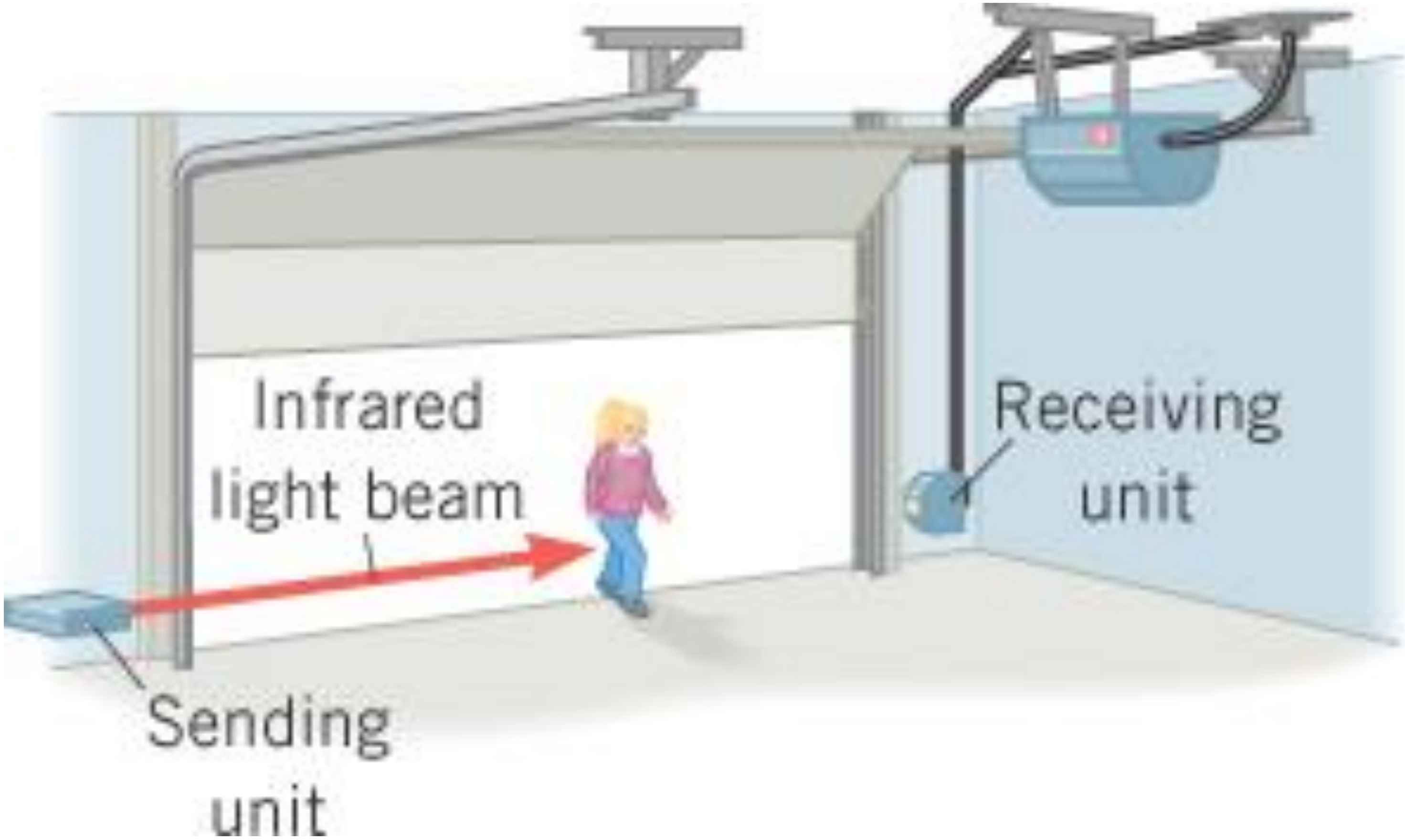
$$hf_o = \underbrace{\mathrm{KE}_{\mathrm{max}}}_{=0\,\mathrm{J}} + W_o$$

$$f_o = \frac{W_o}{h} = \frac{(4.73\,\mathrm{eV})\left(1.60\times10^{-19}\,\mathrm{J/eV}\right)}{6.626\times10^{-34}\,\mathrm{J\cdot s}} = 1.14\times10^{15}\,\mathrm{Hz}$$

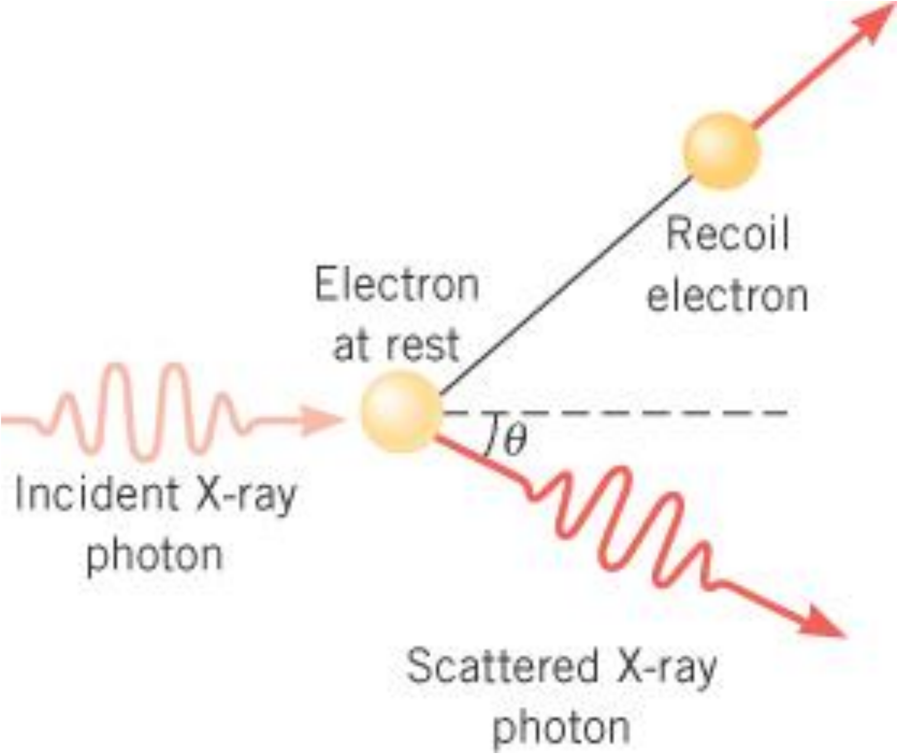
29.3 Photons and the Photoelectric Effect



29.3 Photons and the Photoelectric Effect



29.4 The Momentum of a Photon and the Compton Effect

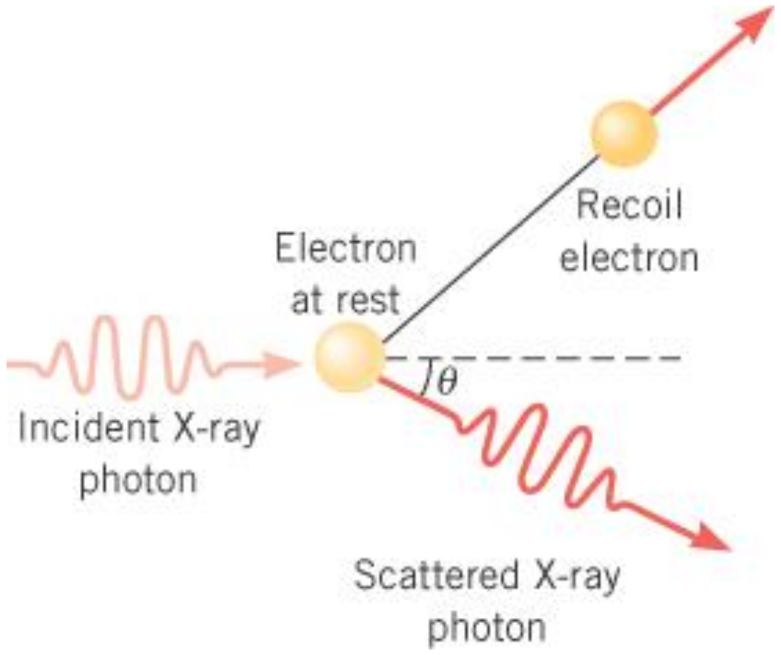


The scattered photon and the recoil electron depart the collision in different directions.

Due to conservation of energy, the scattered photon must have a smaller frequency.

This is called the ***Compton effect.***

29.4 *The Momentum of a Photon and the Compton Effect*

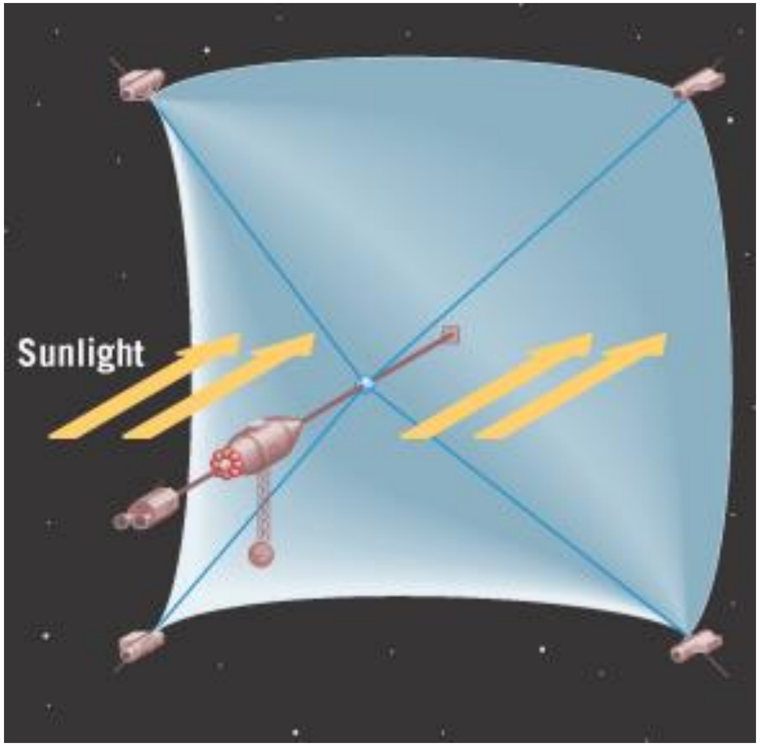


Momentum and energy are conserved in the collision.

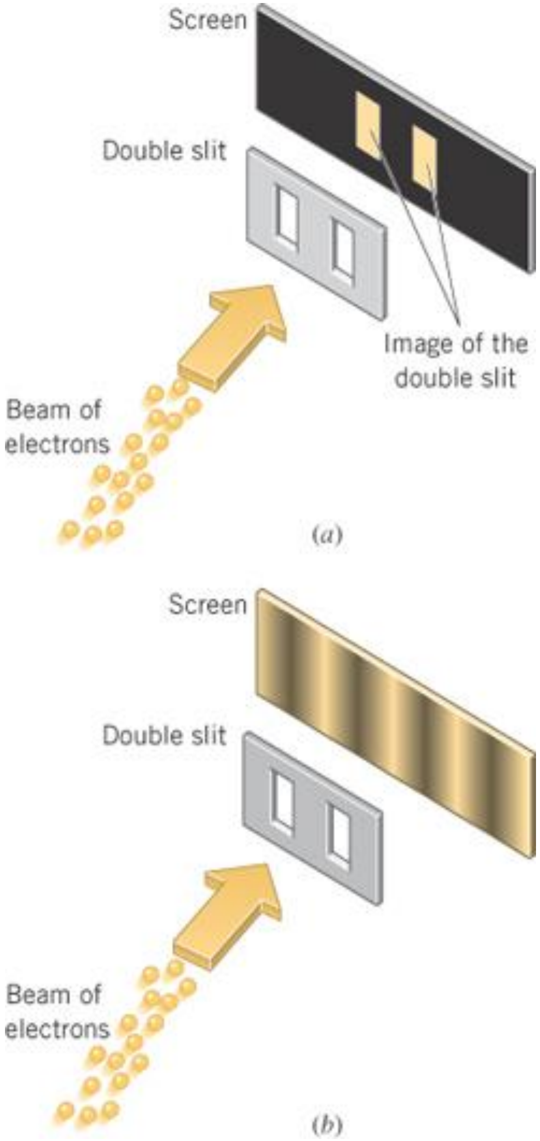
$$\lambda' - \lambda = \frac{h}{mc}\left(1 - \cos\theta\right)$$

Conceptual Example 4 Solar Sails and the Propulsion of Spaceships

One propulsion method that is currently being studied for interstellar travel uses a large sail. The intent is that sunlight striking the sail creates a force that pushes the ship away from the sun, much as wind propels a sailboat. Does such a design have any hope of working and, if so, should the surface facing the sun be shiny like a mirror or black, in order to produce the greatest force?



29.5 *The de Broglie Wavelength and the Wave Nature of Matter*

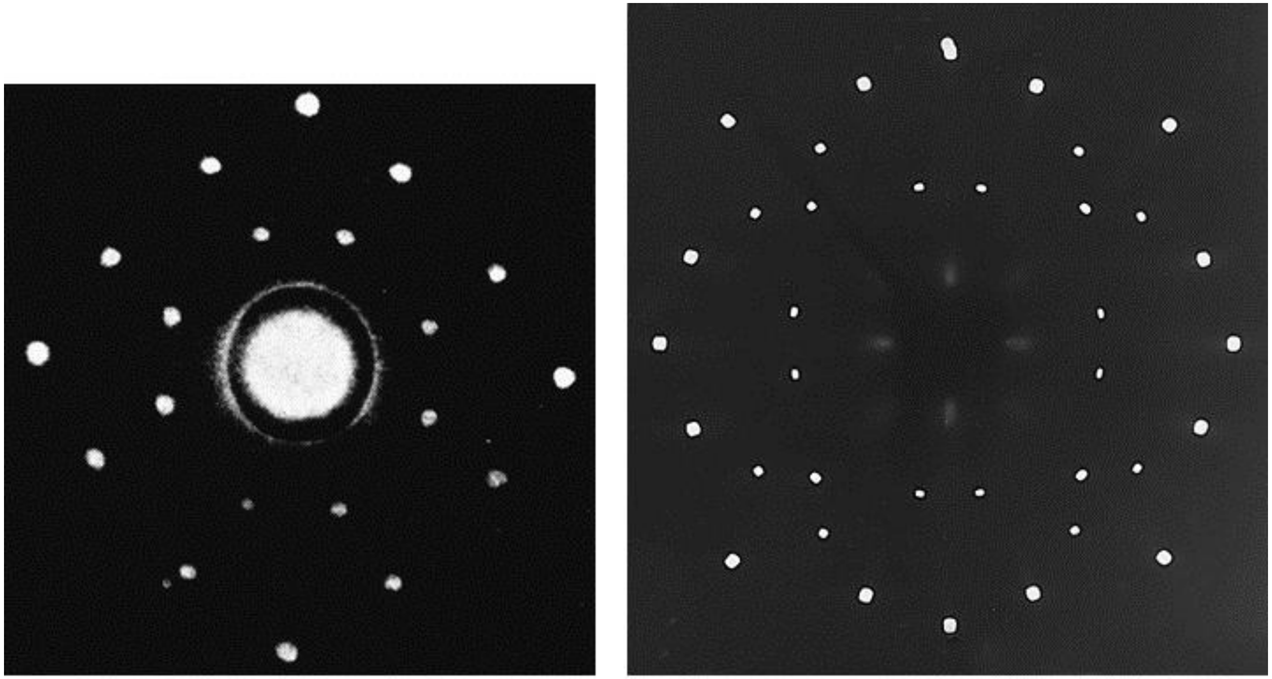


The wavelength of a particle is given by the same relation that applies to a photon:

$$\lambda = h/p$$

de Broglie wavelength

29.5 *The de Broglie Wavelength and the Wave Nature of Matter*



(*a*) (*b*)

Neutron diffraction is a manifestation of the wave-like properties of particles.

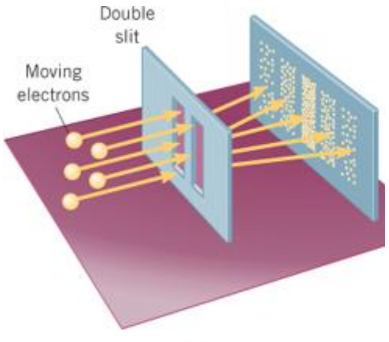
Example 5 **The de Broglie Wavelength of an Electron and a Baseball**

Determine the de Broglie wavelength of (a) an electron moving at a speed of $6.0\text{x}10^6$ m/s and (b) a baseball (mass = 0.15 kg) moving at a speed of 13 m/s.

$$\lambda = h/p = \frac{\left(6.63\times10^{-34}\ \mathrm{J/s}\right)}{\left(9.1\times10^{-31}\mathrm{kg}\right)\left(6.0\times10^{6}\ \mathrm{m/s}\right)} = 1.2\times10^{-10}\mathrm{m}$$

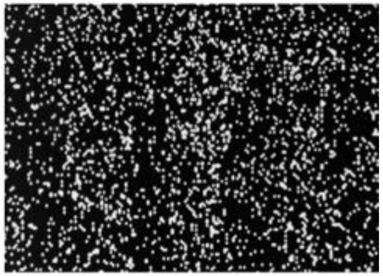
$$\lambda = h/p = \frac{\left(6.63\times10^{-34}\ \mathrm{J/s}\right)}{\left(0.15\ \mathrm{kg}\right)\left(13\,\mathrm{m/s}\right)} = 3.3\times10^{-34}\mathrm{m}$$

29.5 *The de Broglie Wavelength and the Wave Nature of Matter*

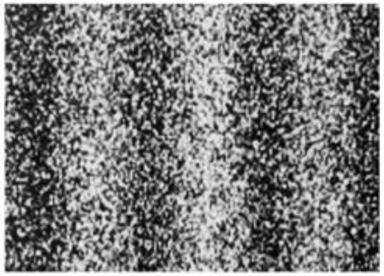


(*a*)

(*b*) After 100 electrons



(*c*) After 3000 electrons



(*d*) After 70 000 electrons

***Particles are waves of probability*.**

THE HEISENBERG UNCERTAINTY PRINCIPLE

Momentum and position

$$\left(\Delta p_y\right)\left(\Delta y\right) \geq \frac{h}{4\pi}$$

Uncertainty in *y* component of the particle’s momentum

Uncertainty in particle’s position along the *y* direction

29.6 *The Heisenberg Uncertainty Principle*

THE HEISENBERG UNCERTAINTY PRINCIPLE

Energy and time

$$(\Delta E)(\Delta t) \geq \frac{h}{4\pi}$$

Uncertainty in the energy
of a particle when the particle
is in a certain state

time interval during
which the particle is
in that state

Conceptual Example 7 What if Planck's Constant Were Large?

A bullet leaving the barrel of a gun is analogous to an electron passing through the single slit. With this analogy in mind, what would hunting be like if Planck's constant has a relatively large value?