Chapter 27

Quantum Theory

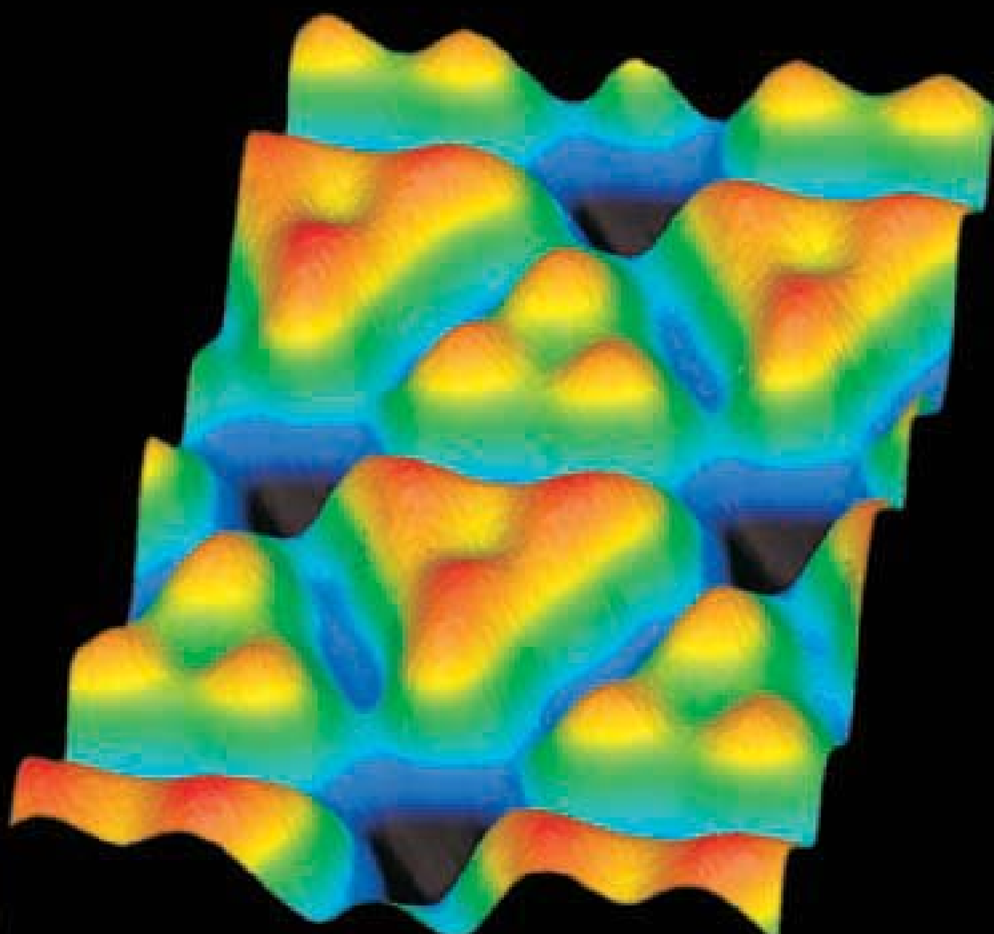
What You'll Learn

- You will understand that light behaves like particles having momentum and energy.
- You will learn that small particles of matter behave like waves and are subject to diffraction and interference.

Why It's Important

Quantum theory provides the basis for an amazing device called a scanning tunneling microscope (STM). The STM is vital to researchers studying DNA and chemical reaction mechanisms. It also is used in the development of smaller and faster computers.

Atomic-Scale Images Two types of silicon atoms, appearing in red and blue, are seen in this STM image of silicon.



Think About This ▶

An STM was used by The Colorado School of Mines to produce this image of the surface of silicon. The STM uses the ability of electrons to jump across a barrier. How does this jump, which is impossible according to the law of conservation of energy, occur?

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photo courtsey of Peter Sutter/Colorado School of Mines

LAUNCH Lab

What does the spectrum of a glowing lightbulb look like?

Question
What colors of visible light are emitted by a glowing, incandescent lightbulb?

Procedure
1. Screw a clear, incandescent lightbulb into a lamp socket.
2. Plug the lamp into an electrical outlet that is controlled by a dimmer switch. Turn the lamp on and dim it so that it glows weakly. ***CAUTION: Do not touch the glowing bulb, as it is very hot and can cause burns.***
3. Dim or turn off the other lights in the classroom.
4. Standing about 1-2 m away from the lightbulb, hold a holographic diffraction grating close to your eye. Observe the lightbulb through the diffraction grating. ***CAUTION: Do not directly view the glowing lightbulb without using the diffraction grating, as damage to your vision may result.***
5. **Make and Use Scientific Illustrations** Use colored pencils to sketch a diagram of what you observe.
6. Turn up the dimmer control to increase the lightbulb to its maximum brightness.
7. **Make and Use Scientific Illustrations** Use colored pencils to sketch a diagram of what you observe.

Analysis
Describe the spectrum emitted by the lightbulb. Is it continuous or a series of distinct colored lines? Describe how the observed spectrum changed when the lightbulb glowed brighter.

Critical Thinking
What is the source of the light emitted by the bulb? What happens to the temperature of the lightbulb's filament when the bulb glows brighter?

27.1 A Particle Model of Waves

James Maxwell's electromagnetic wave theory, which you learned about in the previous chapter, was proven to be correct by the experiments of Heinrich Hertz in 1889. Light was then firmly established as an electromagnetic wave. All of optics, including phenomena such as interference, diffraction, and polarization, seemed to be explainable in terms of the electromagnetic wave theory.

Problems remained for physicists, however, because Maxwell's notion of light as a purely electromagnetic wave could not explain several other important phenomena. These problems generally involved the absorption or emission of electromagnetic radiation. Two such problems were the emission spectrum given off by a hot body (hot object) and the discharge of electrically charged particles from a metal surface when ultraviolet radiation was incident upon it. As you will learn, these phenomena could be explained once it was understood that electromagnetic waves have particle-like properties in addition to wavelike properties.

▶ Objectives
- **Describe** the spectrum emitted by a hot body.
- **Explain** the photoelectric and Compton effects.
- **Solve** problems involving the photoelectric effect.

▶ Vocabulary
emission spectrum
quantized
photoelectric effect
threshold frequency
photon
work function
Compton effect

Radiation from Incandescent Bodies

Why was the radiation emitted from a hot body puzzling to physicists? The problem had to do with the intensity and frequency of the emitted radiation at different temperatures. Maxwell's electromagnetic wave theory could not account for the observed radiation emissions of hot bodies. What then, is the nature of the radiation emitted by hot bodies?

The lightbulb that you observed in the Launch Lab at the start of this chapter is an example of a hot body. As predicted by electromagnetic theory, light and infrared radiation are emitted by the vibrating charged particles within the filament. The filament glows because it is hot, and it is said to be incandescent; hence, the name incandescent lightbulb. The colors that you see depend upon the relative intensities of the emitted electromagnetic waves of various frequencies, and the sensitivity of your eyes to those waves.

When the dimmer control is used to increase the voltage to the bulb, the temperature of the glowing filament increases. As a result, the color changes from deep red to orange to yellow and finally, to white. This color change occurs because the higher-temperature filament emits higher-frequency radiation. The higher-frequency radiation comes from the higher-frequency end of the visible spectrum (the violet end) and results in the filament appearing to be whiter.

What would you expect to see if you viewed the glowing filament through a diffraction grating? When viewed in this way, all of the colors of the rainbow would be visible. The bulb also emits infrared radiation that you would not see. A plot of the intensity of the light emitted from a hot body over a range of frequencies is known as an **emission spectrum.** Emission spectra of the incandescent body at temperatures of 4000 K, 5800 K, and 8000 K are shown in **Figure 27-1.** Note that at each temperature, there is a frequency at which the maximum amount of energy is emitted. If you compare the location of each curve's maximum, you will see that as the temperature increases, the frequency at which the maximum amount of energy is emitted also increases.

MINI LAB

Glows in the Dark

Close the shades and turn off the lights in the room. Shine a flashlight at a beaker that contains fluorescein. Now place a red filter over the flashlight so that only red light hits the beaker.

1. Describe the results.

2. Predict how using a green filter instead of the red filter will affect the results.

3. Test your prediction.

4. Explain the results.

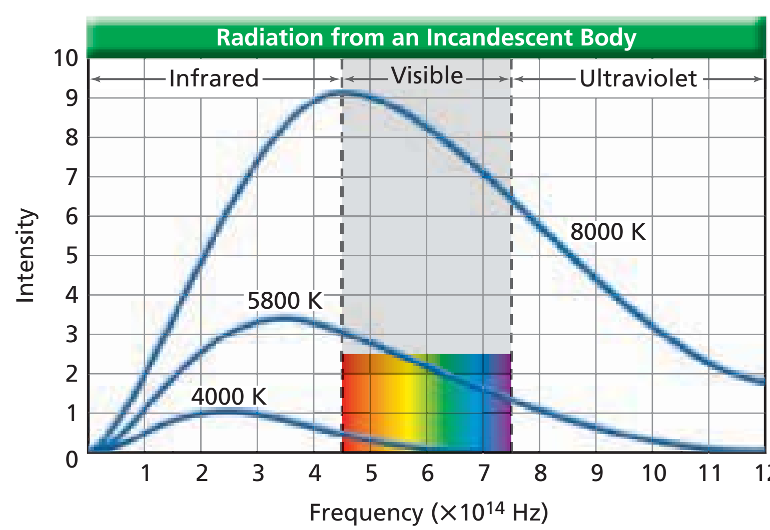
5. Predict whether the fluorescein will glow when a blue filter is used and provide an explanation for your prediction.

6. Test your prediction.

Analyze and Conclude

7. Write a brief explanation summarizing and explaining your observations.

Figure 27-1 This graph shows the emission spectra of an incandescent body at three different temperatures.



The total power emitted by a hot body also increases with temperature. The power (the energy emitted per second) of an electromagnetic wave is proportional to the hot body's kelvin temperature raised to the fourth power, $\propto T^4$. Thus, hotter bodies radiate considerably more power than do cooler bodies. Probably the most common example of a hot body radiating a great amount of power is the Sun, a dense ball of gases heated to incandescence by the energy produced within it. The Sun's surface temperature is 5800 K, and it radiates 4×10^{26} W of power, an enormous quantity. On average, each square meter of Earth's surface receives about 1000 J of energy per second (1000 W), enough to power ten 100-W lightbulbs.

Astronomy Connection

The problem with Maxwell's electromagnetic theory was that it is unable to explain the shape of the spectrum shown in Figure 27-1. Between 1887 and 1900, many physicists used existing classical physics theories to try to explain the shape. They all failed. In 1900, German physicist Max Planck found that he could calculate the spectrum if he introduced a revolutionary hypothesis: that atoms are not able to continuously change their energy. Planck assumed that the vibrational energy of the atoms in a solid could have only specific frequencies, as shown by the following equation.

Energy of Vibration $E = nhf$

The energy of a vibrating atom is equal to the product of an integer, Planck's constant, and the frequency of the vibration.

In the equation, f is the frequency of vibration of the atom, h is a constant, called Planck's constant, with a value of 6.626×10^{-34} J/Hz, and n is an integer such as 0, 1, 2, 3 . . .

$$n = 0:\ E = (0)hf = 0$$
$$n = 1:\ E = (1)hf = hf$$
$$n = 2:\ E = (2)hf = 2hf$$
$$n = 3:\ E = (3)hf = 3hf$$
and so on

Thus, the energy, E, can have the values hf, $2hf$, $3hf$, and so on, but never values such as $\frac{2}{3}hf$ or $\frac{3}{4}hf$. In other words, energy is **quantized**—it exists only in bundles of specific amounts. h is usually rounded to 6.63×10^{-34} J/Hz for calculations.

Planck also proposed that atoms do not always radiate electromagnetic waves when they are vibrating, as predicted by Maxwell. Instead, Planck proposed that atoms emit radiation only when their vibrational energy changes. For example, if the energy of an atom changes from $3hf$ to $2hf$, the atom emits radiation. The energy radiated is equal to the change in energy of the atom, in this case hf.

Planck found that the constant, h, has an extremely small value. This means that the energy-changing steps are too small to be noticeable in ordinary bodies. Still, the introduction of quantized energy was extremely troubling to physicists, especially to Planck himself. It was the first hint that the classical physics of Newton and Maxwell might be valid only under certain conditions. Planck was honored for his groundbreaking theory of quantized energy with a Nobel prize in 1918 and, more recently, with the postage stamp shown in **Figure 27-2.**

APPLYING PHYSICS

Temperature of the Universe The universe is filled with the radiation that was emitted when it was a very hot object. Currently, the emission spectrum of the universe matches that of a body with a temperature of 2.7 K. This is very cold. As you may recall, 0 K is the lowest possible temperature on the Kelvin temperature scale and is known as absolute zero.

Figure 27-2 This stamp honors Max Planck's work and refers to the constant that bears his name, Planck's constant, h. Planck's constant, which has a value of 6.626×10^{-34} J/Hz, is used in many quantum-related equations.

The Photoelectric Effect

Physicists of the early 1900s also were challenged by another troubling experimental result that could not be explained by Maxwell's wave theory. When ultraviolet radiation was incident on a negatively charged zinc plate, the plate discharged. When ordinary visible light was incident on the same charged plate, the plate did not discharge. This result was contrary to electromagnetic theory. Both ultraviolet radiation and visible light are forms of electromagnetic radiation, so why would the zinc plate be discharged by one but not by the other? And why would a positively charged zinc plate not be similarly discharged? Further study showed that the negatively charged zinc plate was discharging by emitting or ejecting electrons. The emission of electrons when electromagnetic radiation falls on an object is called the **photoelectric effect.**

The photoelectric effect can be studied in a photocell, such as the one shown in **Figure 27-3.** The cell contains two metal electrodes sealed in a tube from which the air has been removed. The evacuated tube keeps the metal surfaces from oxidizing and keeps the electrons from being slowed or stopped by particles in the air. The larger electrode, the cathode, usually is coated with cesium or another alkali metal. The smaller electrode, the anode, is made of a thin wire so that it blocks only a very small amount of radiation. The tube often is made of quartz so as to allow ultraviolet wavelengths to pass through it. A potential difference placed across the electrodes attracts electrons to the anode.

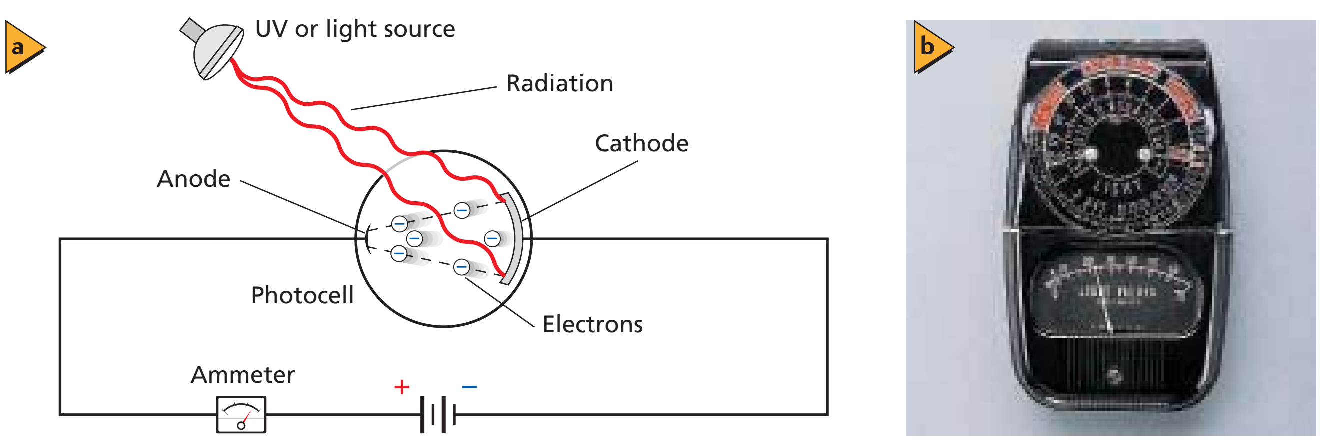
When no radiation falls on the cathode, there is no current in the circuit. When radiation falls on the cathode, a current is produced, which is measured by the ammeter, as shown in Figure 27-3. The current is produced because the photoelectric effect causes the ejection of electrons, also called photoelectrons, from the cathode. The flow of electrons is the current in the circuit. The electrons travel to the anode, the positive electrode.

Threshold frequency Not all radiation falling on the cathode results in a current. Electrons are ejected from the cathode only if the frequency of the radiation is greater than a certain minimum value, called the **threshold frequency,** f_0. The threshold frequency varies widely, depending on the type of metal. For example, all wavelengths of visible light except red will eject electrons from cesium, but no wavelength of visible light will eject electrons from zinc. Higher-frequency ultraviolet radiation is needed to produce the photoelectric effect in zinc.

CLICK HERE

Figure 27-3 In the photocell shown, electrons ejected from the cathode flow to the anode, completing the circuit and generating an electric current **(a).** This handheld light meter works because of the photoelectric effect and is used by photographers to measure light levels **(b).**

Concepts In Motion
Interactive Figure To see an animation on the photoelectric effect, visit **physicspp.com**.



Horizons Companies

No matter how intense, radiation with a frequency below f_0 will not cause the ejection of electrons from metal. Conversely, even very low-intensity radiation with a frequency at or above the threshold frequency causes the immediate ejection of electrons. When the incident radiation's frequency is equal to or greater than the threshold frequency, increasing the intensity of the radiation causes an increase in the flow of photoelectrons.

How does the electromagnetic wave theory explain the photoelectric effect? It can't. According to electromagnetic wave theory, the electric field accelerates and ejects the electrons from the metal, and the strength of the electric field is related to the intensity of the radiation (not to the radiation's frequency). Thus, it follows that electrons in the metal would need to absorb energy from a dim light source for a very long time before they gained enough energy to be ejected. As you just learned, however, this is not the case. Observations show that electrons are ejected immediately when even low-intensity radiation at or above the threshold frequency is incident on the metal.

Photons and quantized energy In 1905, Albert Einstein published a revolutionary theory that explained the photoelectric effect. According to Einstein, light and other forms of electromagnetic radiation consist of discrete, quantized bundles of energy, each of which was later called a **photon.** The energy of a photon depends on its frequency.

Energy of a Photon $E = hf$

The energy of a photon is equal to the product of Planck's constant and the frequency of the photon.

In the above equation, f is frequency in Hz, and h is Planck's constant. Because the unit Hz = 1/s or s^{-1}, the J/Hz unit of Planck's constant is also equivalent to J·s. Because the joule is too large a unit of energy to use with atomic-sized systems, the more convenient energy unit of the electron volt (eV) is usually used. One electron volt is the energy of an electron accelerated across a potential difference of 1 V.

$$
\begin{aligned}
1\ \text{eV} &= (1.60\times10^{-19}\ \text{C})(1\ \text{V}) \\
&= 1.60\times10^{-19}\ \text{C·V} \\
&= 1.60\times10^{-19}\ \text{J}
\end{aligned}
$$

Using the definition of an electron volt allows the photon energy equation to be rewritten in a simplified form, as shown below.

Energy of a Photon $E = \frac{hc}{\lambda} = \frac{1240\ \text{eV·nm}}{\lambda}$

The energy of a photon is equal to the constant 1240 eV·nm divided by the wavelength of the photon.

An explanation of the derivation of this equation and how to use it is given in the Problem-Solving Strategies on the next page.

Physics Online

Personal Tutor For an online tutorial on units of *hc* and photon energy, visit physicspp.com.

PROBLEM-SOLVING Strategies

Units of *hc* and Photon Energy

Connecting Math to Physics

Converting the quantity hc to the unit eV·nm results in a simplified equation that can be used to solve problems involving photon wavelength.

1. The energy of a photon of wavelength λ is given by the equation $E = hf$.
2. Because $f = c/\lambda$, this equation can be written as $E = hc/\lambda$.
3. When using the equation $E = hc/\lambda$, if the value of hc in eV·nm is divided by λ in nm, you will obtain the energy in eV. Thus, it is useful to know the value of hc in eV·nm.
4. The conversion of hc to the unit eV·nm is as follows:

$$hc = (6.626\times10^{-34}\text{ J/Hz})(2.998\times10^{8}\text{ m/s})\left(\frac{1\text{ eV}}{1.602\times10^{-19}\text{ J}}\right)\left(\frac{10^{9}\text{ nm}}{1\text{ m}}\right)$$

$$= 1240\text{ eV}$$

5. Substituting $hc = 1240$ eV·nm into the equation for the energy of a photon yields the following, where λ is in nm and E is in eV:

$$E = \frac{hc}{\lambda} = \frac{1240\text{ eV}\cdot\text{nm}}{\lambda}$$

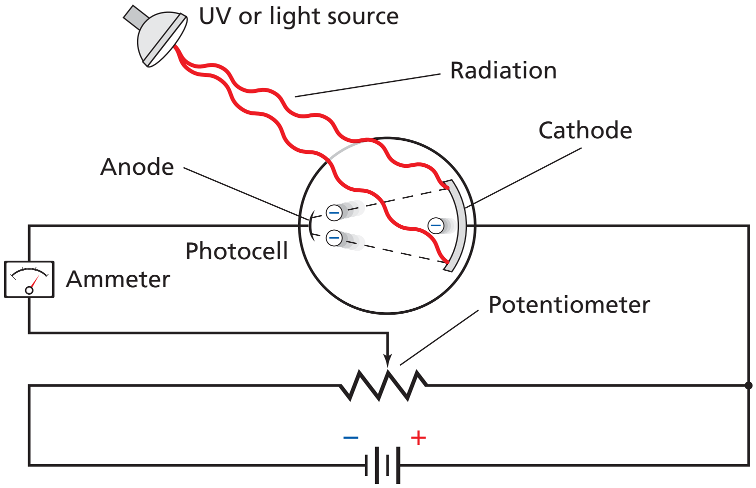
6. Use the above equation to solve photon energy problems when energy in eV is desired.

It is important to note that Einstein's theory of the photon goes further than Planck's theory of radiation from hot bodies. While Planck had proposed that vibrating atoms emit electromagnetic radiation with energy equal to *nhf*, he did not suggest that light and other forms of electromagnetic radiation act like particles. Einstein's theory of the photon reinterpreted and extended Planck's theory of radiation from hot bodies.

Einstein's photoelectric-effect theory is able to explain the existence of a threshold frequency. A photon with a minimum frequency and energy, hf_0, is needed to eject an electron from metal. If the photon has a frequency below f_0, the photon will not have the energy needed to eject an electron. Because one photon interacts with one electron, an electron cannot simply accumulate subthreshold energy photons until it has enough energy to be ejected. On the other hand, radiation with a frequency greater than f_0 has more than enough energy to eject an electron. In fact, the excess energy, $hf - hf_0$, becomes the kinetic energy of the ejected electron.

Kinetic Energy of an Electron Ejected Due to the Photoelectric Effect $KE = hf - hf_0$

The kinetic energy of an ejected electron is equal to the difference between the incoming photon energy, hf, and the energy needed to free the electron from the metal, hf_0.



■ **Figure 27-4** The maximum kinetic energy of electrons ejected from the cathode can be measured using this apparatus. The ammeter measures the current through the circuit. By adjusting the potentiometer, the experimenter can determine the potential that results in zero current. At the zero current threshold, the maximum possible kinetic energy of the ejected electron can be calculated.

Note that hf_0 is the minimum energy needed to free the most loosely held electron in an atom. Because not all electrons in an atom have the same energy, some will require more than this minimum energy in order to escape. As a result, the ejected electrons have differing kinetic energies. Thus, it is important to realize that the phrase "kinetic energy of the ejected electrons" refers to the maximum kinetic energy that an ejected electron could have. Some of the ejected electrons will have less.

Testing the photoelectric theory How can Einstein's theory be tested? The kinetic energy of the ejected electrons can be measured indirectly by a device like the one illustrated in **Figure 27-4.** A variable electric potential difference is used to adjust the voltage across the tube. When the potential difference is adjusted to make the anode negative, the ejected electrons must expend energy to reach the anode. Only electrons ejected from the cathode with sufficient kinetic energy will be able to reach the anode.

As shown in Figure 27-4, light of the chosen frequency illuminates the cathode. Gradually, the experimenter increases the opposing potential difference, thereby making the anode more negative. As the opposing potential difference increases, more kinetic energy is needed for the electrons to reach the anode, and fewer electrons arrive there to complete the circuit. At a certain voltage, called the stopping potential, there are no electrons with enough kinetic energy to reach the anode, and the current stops.

At the stopping potential, the kinetic energy of the electrons at the cathode equals the work done by the electric field to stop them. This is represented in equation form as $KE = -qV_0$. In this equation, V_0 is the magnitude of the stopping potential in volts (J/C), and q is the charge of the electron (-1.60×10^{-19} C). Note that the negative sign in the equation along with the negative value of q yield a positive value for KE.

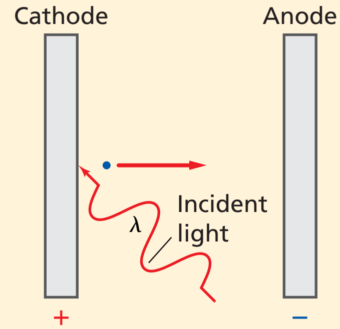
Applications The photoelectric effect is used in a variety of everyday applications. Solar panels, shown in **Figure 27-5,** use the photoelectric effect to convert the Sun's light into electricity. Garage-door openers have safety beams of infrared light that create current in the receiver through the photoelectric effect. If the beam of light is interrupted by an object as the garage door is closing, the current in the receiver stops and triggers the opener to open the door. The photoelectric effect also is used in nightlights and photo eyes that turn lights on and off automatically, depending on whether it is day or night.

■ **Figure 27-5** The solar panels on this building use the photoelectric effect to convert the Sun's light to electricity.

Ruth Dixon

▶ EXAMPLE Problem 1

Photoelectron Kinetic Energy The stopping potential of a certain photocell is 4.0 V. What is the kinetic energy given to the electrons by the incident light? Give your answer in both joules and electron volts.



1 Analyze and Sketch the Problem

- Draw the cathode and anode, the incident radiation, and the direction of the ejected electron. Note that the stopping potential prevents electrons from flowing across the photocell.

Known:

$V_0 = 4.0$ V

$q = -1.60\times10^{-19}$ C

Unknown:

KE (in J and eV) = ?

2 Solve for the Unknown

The electric field does work on the electrons. When the work done, W, equals the negative of the initial kinetic energy, KE, electrons no longer flow across the photocell.

$$KE + W = 0 \text{ J}$$

Solve for KE.

$$KE = -W$$

$$= -qV_0 \qquad \textbf{Substitute } W = qV_0$$

$$= -(-1.60\times10^{-19}\text{ C})(4.0\text{ V}) \qquad \textbf{Substitute } q = -1.60\times10^{-19}\text{ C}, V_0 = 4.0\text{ V}$$

$$= +6.4\times10^{-19}\text{ J}$$

Convert KE from joules to electron volts.

$$KE = (6.4\times10^{-19}\text{ J})\left(\frac{1\text{ eV}}{1.60\times10^{-19}\text{ J}}\right)$$

$$= 4.0\text{ eV}$$

Math Handbook
Operations with Scientific Notation
pages 842–843

3 Evaluate the Answer

- **Are the units correct?** Joules and electron volts are both units of energy.
- **Does the sign make sense?** Kinetic energy is always positive.
- **Is the magnitude realistic?** The energy in electron volts is equal in magnitude to the stopping potential difference in volts.

▶ PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

1. An electron has an energy of 2.3 eV. What is the energy of the electron in joules?
2. What is the energy in eV of an electron with a velocity of 6.2×10^{6} m/s?
3. What is the velocity of the electron in problem 1?
4. The stopping potential for a photoelectric cell is 5.7 V. Calculate the maximum kinetic energy of the emitted photoelectrons in eV.
5. The stopping potential required to prevent current through a photocell is 3.2 V. Calculate the maximum kinetic energy in joules of the photoelectrons as they are emitted.

CHALLENGE PROBLEM

Suppose a nickel with a mass of 5.0 g vibrates up and down while it is connected to a spring. The maximum velocity of the nickel during the oscillations is 1.0 cm/s. Assume that the vibrating nickel models the quantum vibrations of the electrons within an atom, where the energy of the vibrations is given by the equation $E = nhf$.

1. Find the maximum kinetic energy of the vibrating object.

2. The vibrating object emits energy in the form of light with a frequency of 5.0×10^{14} Hz. If the energy is emitted in a single step, find the energy lost by the object.

3. Determine the number of equally sized energy-step reductions that the object would have to make in order to lose all of its energy.

Mass = 5.0 g
Maximum velocity = 1.0 cm/s

A graph of the kinetic energies of the electrons ejected from a metal versus the frequencies of the incident photons is a straight line, as shown in **Figure 27-6.** All metals have similar graphs with the same slope. This slope equals the rise/run ratio of the line, which is equal to Planck's constant, h.

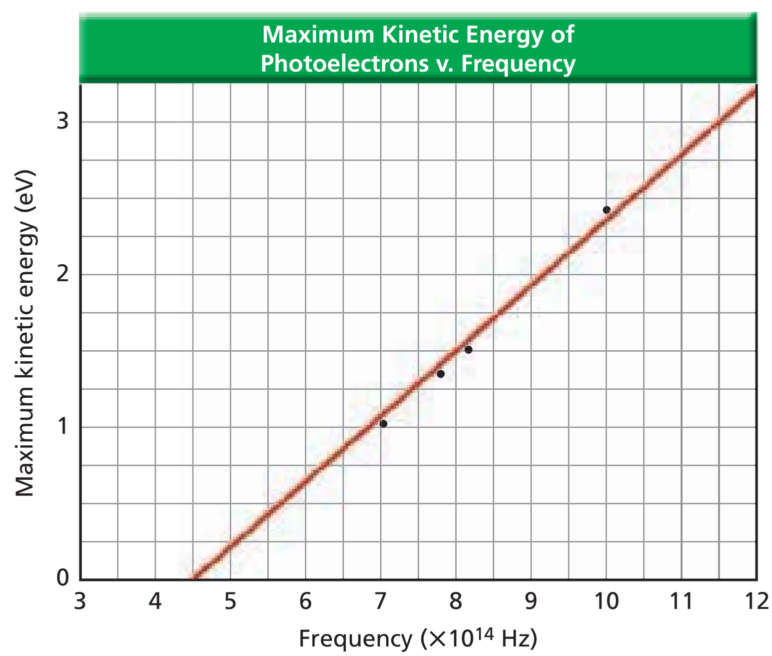
$$\text{slope} = \frac{\text{rise}}{\text{run}} = \frac{\text{change in maximum kinetic energy of ejected electrons}}{\text{change in frequency of incident radiation}}$$

$$= \frac{\Delta KE}{f} = h$$

The graphs of various metals differ only in the threshold frequency needed to free the electrons. In Figure 27-6, the threshold frequency, f_0, is the point at which $KE = 0$. In this case, f_0, located at the intersection of the line with the x-axis, is approximately 4.4×10^{14} Hz. The threshold frequency is related to the work function of the metal. The **work function** of a metal is the energy needed to free the most weakly bound electron from the metal. The magnitude of the work function is equal to hf_0. When a photon of frequency f_0 is incident on a metal, the energy of the photon is sufficient to release the electron, but not sufficient to provide the electron with any kinetic energy.

Between 1905 and 1916, American physicist Robert Millikan performed a brilliant set of experiments in which he attempted to disprove Einstein's photoelectric theory. While his results confirmed Einstein's equation, he did not accept Einstein's "radical" notion of the photon. Millikan's experiments made it possible for Einstein to receive a Nobel prize for his photoelectric theory in 1921. Two years later, in 1923, Millikan was awarded a Nobel prize for determining the charge of an electron and for his investigations into the photoelectric effect.

■ **Figure 27-6** This graph shows that as the frequency of the incident radiation increases, the kinetic energy of the ejected electrons increases proportionally.

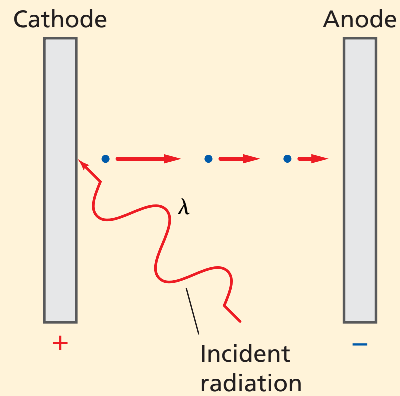


▶ EXAMPLE Problem 2

Work Function and Energy A photocell uses a sodium cathode. The sodium cathode has a threshold wavelength of 536 nm.

a. Find the work function of sodium in eV.

b. If ultraviolet radiation with a wavelength of 348 nm falls on sodium, what is the energy of the ejected electrons in eV?



1 Analyze and Sketch the Problem

- Draw the cathode and anode, the incident radiation, and the direction of the ejected electron.

Known:		**Unknown:**	
$\lambda_0 = 536$ nm	$\lambda = 348$ nm	$W = ?$	$KE = ?$
$hc = 1240$ eV·nm			

2 Solve for the Unknown

a. Find the work function using Planck's constant and the threshold wavelength.

$$W = hf_0 = \frac{hc}{\lambda_0}$$

$$= \frac{1240 \text{ eV·nm}}{536 \text{ nm}}$$ **Substitute hc = 1240 eV·nm, λ_0 = 536 nm**

$$= 2.31 \text{ eV}$$

b. Use Einstein's photoelectric-effect equation to determine the energy of the incident radiation.

$$E = \frac{1240 \text{ eV·nm}}{\lambda}$$

$$= \frac{1240 \text{ eV·nm}}{348 \text{ nm}}$$ **Substitute λ = 348 nm**

$$= 3.56 \text{ eV}$$

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Operations with Significant Digits
pages 835–836

To calculate the energy of the ejected electron, subtract the work function from the energy of the incident radiation.

$$KE = hf - hf_0 = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$$

$$= E - W$$ **Substitute $\frac{hc}{\lambda} = E$, $\frac{hc}{\lambda_0} = W$**

$$= 3.56 \text{ eV} - 2.31 \text{ eV}$$ **Substitute E = 3.56 eV, W = 2.31 eV**

$$= 1.25 \text{ eV}$$

3 Evaluate the Answer

- **Are the units correct?** Performing dimensional analysis on the units verifies that eV is the proper unit for *KE*.
- **Does the sign make sense?** *KE* is always positive.
- **Are the magnitudes realistic?** Energies should be a few electron volts.

▶ PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

6. The threshold wavelength of zinc is 310 nm. Find the threshold frequency, in Hz, and the work function, in eV, of zinc.

7. The work function for cesium is 1.96 eV. What is the kinetic energy, in eV, of photoelectrons ejected when 425-nm violet light falls on the cesium?

8. When a metal is illuminated with 193-nm ultraviolet radiation, electrons with energies of 3.5 eV are emitted. What is the work function of the metal?

9. A metal has a work function of 4.50 eV. What is the longest-wavelength radiation that will cause it to emit photoelectrons?

The Compton Effect

The photoelectric effect demonstrates that a photon, even though it has no mass, has kinetic energy just as a particle does. In 1916, Einstein predicted that the photon should have another particle property: momentum. He showed that the momentum of a photon should be equal to E/c. Because $E = hf$ and $f/c = 1/\lambda$, the photon's momentum is given by the following equation.

Photon Momentum $p = \frac{hf}{c} = \frac{h}{\lambda}$

The momentum of a photon is equal to Planck's constant divided by the photon's wavelength.

Experiments done by an American physicist, Arthur Holly Compton, in 1922 tested Einstein's theory. The results of Compton's experiments further supported the particle model of light. Compton directed X rays of a known wavelength at a graphite target, as shown in **Figure 27-7a,** and measured the wavelengths of the X rays scattered by the target. He observed that some of the X rays were scattered without change in wavelength, whereas others had a longer wavelength than that of the original radiation. These results are shown in **Figure 27-7b.** Note that the peak wavelength for the unscattered X rays corresponds to the wavelength of the original incident X rays, whereas the peak wavelength for the scattered X rays is greater than that of the original incident X rays.

Recall that the equation for the energy of a photon, $E = hf$, also can be written as $E = hc/\lambda$. This second equation shows that the energy of a photon is inversely proportional to its wavelength. The increase in wavelength that Compton observed meant that the X-ray photons had lost both energy and momentum. The shift in the energy of scattered photons is called the **Compton effect.** This shift in energy is very small, only about 10^{-3} nm, and is a measurable effect only when X rays having wavelengths of 10^{-2} nm or less are used.

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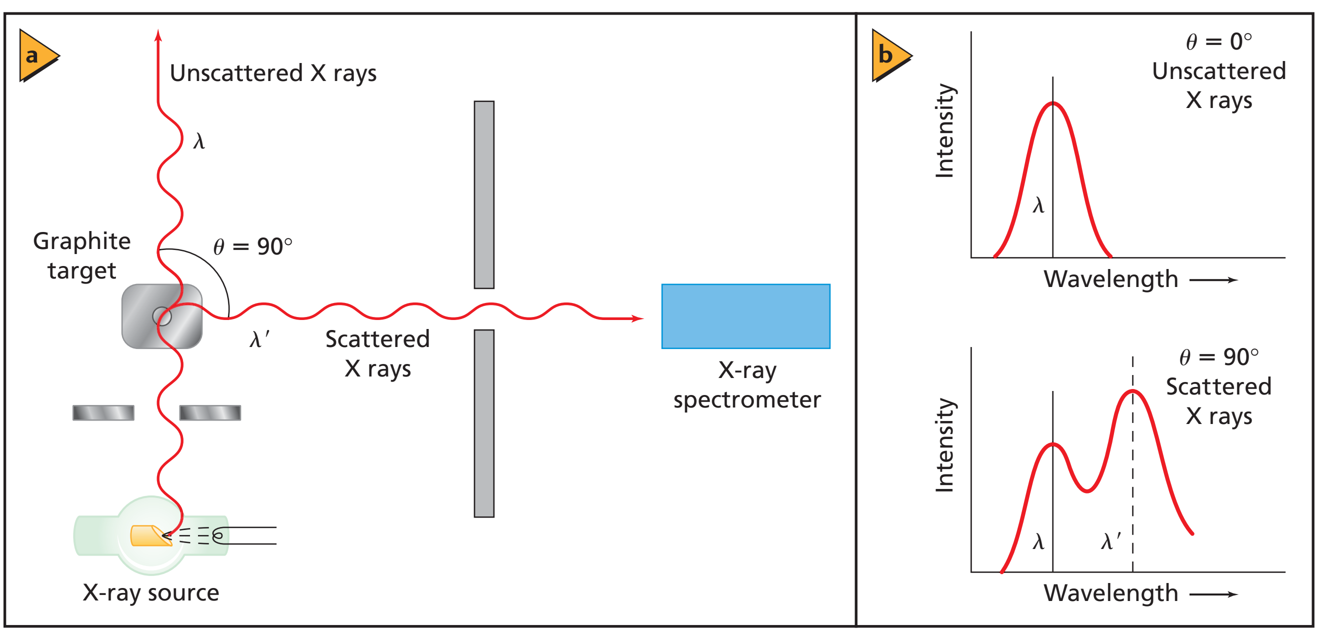
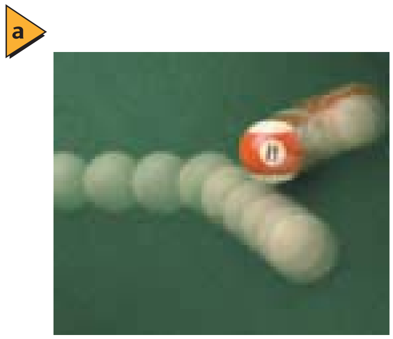
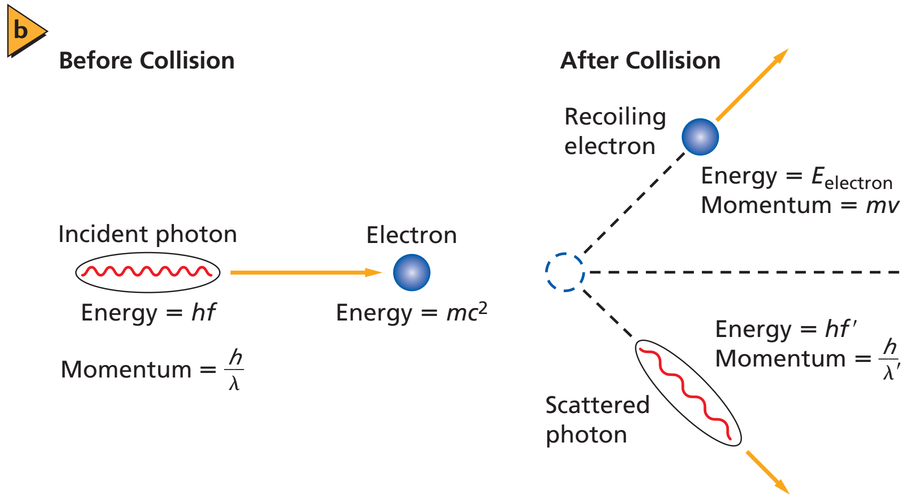


Figure 27-7 Compton used an apparatus similar to this one to study the nature of photons **(a).** The increased wavelength of the scattered photons is evidence that the X-ray photons have lost energy **(b).**





■ **Figure 27-8** Much like the collision between two billiard balls **(a),** when a photon strikes an electron, the energy and momentum gained by the electron equal the energy and momentum lost by the photon **(b).**

In later experiments, Compton observed that electrons were ejected from the graphite block during the experiment. He suggested that the X-ray photons collided with electrons in the graphite target and transferred energy and momentum to them. Compton thought that these photon-electron collisions were similar to the elastic collisions experienced by billiard balls, as shown in **Figure 27-8.** He tested this idea by measuring the energy of the ejected electrons. Compton found that the energy and momentum gained by the electrons equaled the energy and momentum lost by the photons. Thus, photons obey the laws of conservation of momentum and energy when they are involved in collisions with other particles.

27.1 Section Review

10. Photoelectric Effect Why is high-intensity, low-frequency light unable to eject electrons from a metal, whereas low-intensity, high-frequency light can? Explain.

11. Frequency and Energy of Hot-Body Radiation As the temperature of a body is increased, how does the frequency of peak intensity change? How does the total amount of radiated energy change?

12. Photoelectric and Compton Effects An experimenter sends an X ray into a target. An electron, but no other radiation, emerges from the target. Explain whether this event is a result of the photoelectric effect or the Compton effect.

13. Photoelectric and Compton Effects Distinguish the photoelectric effect from the Compton effect.

14. Photoelectric Effect Green light ($\lambda = 532$ nm) strikes an unknown metal, causing electrons to be ejected. The ejected electrons can be stopped by a potential of 1.44 V. What is the work function, in eV, of the metal?

15. Energy of a Photon What is the energy, in eV, of the photons produced by a laser pointer having a 650-nm wavelength?

16. Photoelectric Effect An X ray is absorbed in a bone and releases an electron. If the X ray has a wavelength of approximately 0.02 nm, estimate the energy, in eV, of the electron.

17. Compton Effect An X ray strikes a bone, collides with an electron, and is scattered. How does the wavelength of the scattered X ray compare to the wavelength of the incoming X ray?

18. Critical Thinking Imagine that the collision of two billiard balls models the interaction of a photon and an electron during the Compton effect. Suppose the electron is replaced by a much more massive proton. Would this proton gain as much energy from the collision as the electron does? Would the photon lose as much energy as it does when it collides with the electron?

Physics Online physicspp.com/self_check_quiz

27.2 Matter Waves

The photoelectric effect and Compton scattering showed that a massless electromagnetic wave has momentum and energy, like a particle. If an electromagnetic wave has particlelike properties, could a particle exhibit interference and diffraction, as a wave does? In other words, does a particle have wavelike properties? In 1923, French physicist Louis de Broglie proposed just this, that material particles have wave properties. This proposal was so extraordinary that it was ignored by other scientists until Einstein read de Broglie's papers and supported his ideas.

▶ **Objectives**

- **Describe** evidence of the wave nature of matter.
- **Solve** problems involving the de Broglie wavelength of particles.
- **Describe** the dual nature of waves and particles, and the importance of the Heisenberg uncertainty principle.

▶ **Vocabulary**

de Broglie wavelength
Heisenberg uncertainty principle

De Broglie Waves

Recall that the momentum of an object is equal to its mass times its velocity, $p = mv$. By analogy with the momentum of a photon, $p = h/\lambda$, de Broglie proposed that the momentum of a particle is represented by the following equation:

$$p = mv = \frac{h}{\lambda}$$

The wavelength in the above relationship represents that of the moving particle and is known as the **de Broglie wavelength.** The following equation solves directly for the de Broglie wavelength.

De Broglie Wavelength $\lambda = \frac{h}{p} = \frac{h}{mv}$

The de Broglie wavelength of a moving particle is equal to Planck's constant divided by the particle's momentum.

According to de Broglie, particles such as electrons and protons should show wavelike properties. Effects such as diffraction and interference had never been observed for particles, so de Broglie's work was greeted with considerable doubt. In 1927, however, the results of two independent experiments proved that electrons are diffracted just as light is. In one experiment, English physicist George Thomson aimed a beam of electrons at a very thin crystal. Atoms in crystals are arrayed in a regular pattern that acts as a diffraction grating. Electrons diffracted from the crystal formed the same patterns that X rays of a similar wavelength formed. **Figure 27-9** shows the pattern made by diffracting electrons. In the United States, Clinton Davisson and Lester Germer performed a similar experiment using electrons reflected and diffracted from thick crystals. The two experiments proved that material particles have wave properties.

Figure 27-9 Electron diffraction patterns, such as this one for a cubic zirconium crystal, demonstrate the wave properties of particles.

Max Kurtz/Ztek

The wave nature of objects you see and handle every day is not observable because their wavelengths are extremely short. For example, consider the de Broglie wavelength of a 0.145-kg baseball when it leaves a bat with a speed of 38 m/s.

$$\lambda = \frac{h}{mv} = \frac{6.63\times10^{-34}\ \text{J}\cdot\text{s}}{(0.145\ \text{kg})(38\ \text{m/s})} = 1.2\times10^{-34}\ \text{m}$$

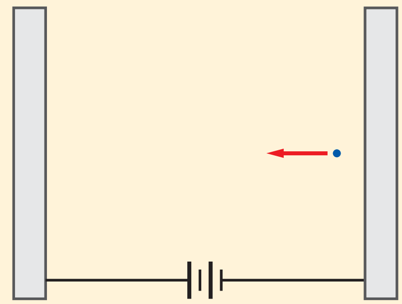
This wavelength is far too small to have observable effects. As you will see in the following Example Problem, however, an extremely small particle, such as an electron, has a wavelength that can be observed and measured.

EXAMPLE Problem 3

De Broglie Wavelength An electron is accelerated by a potential difference of 75 V. What is its de Broglie wavelength?

1 Analyze and Sketch the Problem

- Include the positive and negative plates in your drawing.



Known:		Unknown:
$V = 75$ V	$m = 9.11\times10^{-31}$ kg	$\lambda = ?$
$q = -1.60\times10^{-19}$ C	$h = 6.63\times10^{-34}$ J·s	

2 Solve for the Unknown

Write relationships for the kinetic energy of the electron based on potential difference and motion and use them to calculate the electron's velocity.

$KE = -qV$, and $KE = \frac{1}{2}mv^2$

$\frac{1}{2}mv^2 = -qV$ — Equate both forms of *KE*.

Math Handbook
Isolating a Variable
page 845

Solve for *v*.

$$v = \sqrt{\frac{-2qV}{m}}$$

$$= \sqrt{\frac{-2(-1.60\times10^{-19}\ \text{C})(75\ \text{V})}{9.11\times10^{-31}\ \text{kg}}}$$ Substitute $q = -1.60\times10^{-19}$ C, $V = 75$ V, $m = 9.11\times10^{-31}$ kg

$$= 5.1\times10^{6}\ \text{m/s}$$

Solve for momentum, *p*.

$$p = mv$$

$$= (9.11\times10^{-31}\ \text{kg})(5.1\times10^{6}\ \text{m/s})$$ Substitute $m = 9.11\times10^{-31}$ kg, $v = 5.1\times10^{6}$ m/s

$$= 4.6\times10^{-24}\ \text{kg·m/s}$$

Solve for the de Broglie wavelength, λ.

$$\lambda = \frac{h}{p}$$

$$= \frac{6.63\times10^{-34}\ \text{J·s}}{4.6\times10^{-24}\ \text{kg·m/s}}$$ Substitute $h = 6.63\times10^{-34}$ J·s, $p = 4.6\times10^{-24}$ kg·m/s

$= 1.4\times10^{-10}$ m, which is equivalent to 0.14 nm

3 Evaluate the Answer

- **Are the units correct?** Dimensional analysis on the units verifies m/s for *v* and nm for λ.
- **Do the signs make sense?** Positive values are expected for both *v* and λ.
- **Are the magnitudes realistic?** The wavelength is close to 0.1 nm, which is in the X-ray region of the electromagnetic spectrum.

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

19. A 7.0-kg bowling ball rolls with a velocity of 8.5 m/s.

a. What is the de Broglie wavelength of the bowling ball?

b. Why does the bowling ball exhibit no observable wave behavior?

20. What is the de Broglie wavelength and speed of an electron accelerated by a potential difference of 250 V?

21. What voltage is needed to accelerate an electron so it has a 0.125-nm wavelength?

22. The electron in Example Problem 3 has a de Broglie wavelength of 0.14 nm. What is the kinetic energy, in eV, of a proton ($m = 1.67\times10^{-27}$ kg) with the same wavelength?

Particles and Waves

Is light a particle or a wave? Evidence suggests that both particle and wave models are needed to explain the behavior of light. As you are about to discover, quantum theory and the dual nature of electromagnetic radiation led to fascinating scientific principles and applications. One such application, the scanning tunneling microscope (STM), is discussed in the How it Works feature on page 740.

Determining location and momentum It is logical to think that to accurately define the properties of an object, you would need to devise an experiment that directly measures the desired properties. For example, you cannot simply state that a particle is at a certain location moving with a specific speed. Rather, an experiment must be performed that locates the particle and measures its speed.

How can you detect the location of a particle? You must touch it or reflect light from it. If light is used, then the reflected light must be collected by an instrument or the human eye. Because of diffraction effects, the light used to detect the particle spreads out and makes it impossible to locate the particle exactly. The use of shorter-wavelength light or radiation decreases diffraction and allows the location of a particle to be more precisely measured.

Heisenberg uncertainty principle As a result of the Compton effect, however, when short-wavelength, high-energy radiation strikes a particle, the particle's momentum is changed, as shown in **Figure 27-10.** Therefore, the act of precisely measuring the location of a particle has the effect of changing the particle's momentum. The more precise the determination of a particle's location, the greater the uncertainty is in its momentum. In the same way, if the momentum of the particle is measured, the position of the particle changes and becomes less certain. This situation is summarized by the **Heisenberg uncertainty principle,** which states that it is impossible to measure precisely both the position and momentum of a particle at the same time. This principle, named for German physicist Werner Heisenberg, is the result of the dual wave and particle properties of light and matter. The Heisenberg uncertainty principle tells us there is a limit to how accurately position and momentum can be measured.

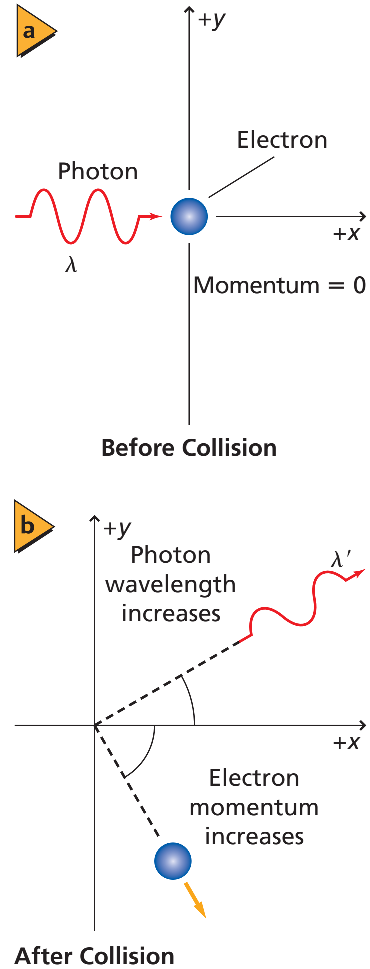


Figure 27-10 A particle can be seen only when light is scattered from it. Thus, the electron remains undetected **(a)** until an incident photon strikes it **(b).** The collision scatters the photon and electron and changes their momenta.

27.2 Section Review

23. Wavelike Properties Describe the experiment that confirmed that particles have wavelike properties.

24. Wave Nature Explain why the wave nature of matter is not obvious.

25. De Broglie Wavelength What is the de Broglie wavelength of an electron accelerated through a potential difference of 125 V?

26. Wavelengths of Matter and Radiation When an electron collides with a massive particle, the electron's velocity and wavelength decrease. How is it possible to increase the wavelength of a photon?

27. Heisenberg Uncertainty Principle When light or a beam of atoms passes through a double slit, an interference pattern forms. Both results occur even when atoms or photons pass through the slits one at a time. How does the Heisenberg uncertainty principle explain this?

28. Critical Thinking Physicists recently made a diffraction grating of standing waves of light. Atoms passing through the grating produce an interference pattern. If the spacing of the slits in the grating were $\frac{1}{2}\lambda$ (about 250 nm), what was the approximate de Broglie wavelength of the atoms?

PhysicsOnline physicspp.com/self_check_quiz

PHYSICS LAB

Modeling the Photoelectric Effect

The emission of electrons from an object when electromagnetic radiation is incident upon it is known as the photoelectric effect. Electrons are ejected from the object only when the frequency of the radiation is greater than a certain minimum value, called the threshold frequency. In this investigation you will model the photoelectric effect using steel balls. You will examine why only certain types of electromagnetic radiation result in the emission of photoelectrons.

QUESTION

How can steel balls be used to model the photoelectric effect?

Objectives

- **Formulate a model** to investigate the photoelectric effect.
- **Describe** how the energy of a photon is related to its frequency.
- **Use scientific explanations** to explain why macroscopic phenomena cannot explain the quantum behavior of the atom.

Safety Precautions

- **Keep isopropyl alcohol away from open flame.**
- **Do not swallow isopropyl alcohol.**
- **Isopropyl alcohol can dry out skin.**

Materials

steel balls (3)
grooved channel (U-channel or shelf bracket)
books
red, orange, yellow, green, blue, and violet marking pens (or colored stickers)
metric ruler
isopropyl alcohol

Procedure

1. Shape the grooved channel, as shown in the photo, and use several books to support the channel, as shown. Make sure the books do not block the ends of the channel.
2. Mark a capital letter *R* with a red marking pen on the channel 4 cm above the table, as shown. The *R* represents red.
3. Mark a capital letter *V* with a violet marking pen on the channel at a distance 14 cm above the table as shown. The *V* represents violet. Use the other colored pens to place marks for blue, *B,* green, *G,* yellow, *Y,* and orange, *O,* uniformly between the marks for *R* and *V.*
4. Place two steel balls at the lowest point on the channel. These steel balls represent the atom's valence electrons.
5. Hold a steel ball in place on the channel at the *R* position. This steel ball represents an incident photon of red light. Note that the red photon has the lowest energy of the six colors of light being modeled.
6. Release the steel ball (photon) and see if it has enough energy to remove a valence electron from the atom; that is, observe if either of the two steel ball electrons escapes from the channel. Record your observations in the data table.

Data Table	
Color or Energy of Photon	**Observations**
Red	
Orange	
Yellow	
Green	
Blue	
Violet	
Less than red	
Greater than violet	

7. Remove the steel ball that represents the incident photon from the lower part of the channel. Replace the two steel balls used to represent the valence electrons at the lowest point on the channel.
8. Repeat steps 5–7 for each of the colors you marked on the channel. Be sure always to start with the two steel balls at the lowest point on the channel. Note that the violet photon has the greatest energy of the six colors of light being modeled. Record your observations in the data table.
9. Repeat steps 5–7, but release the steel ball representing the incident photon from a point slightly lower than the *R* position. Record your observations in the data table.
10. Repeat steps 5–7, but release the steel ball representing the incident photon from a point slightly higher than the *V* position. Record your observations in the data table.
11. Answer question 1 in the Conclude and Apply section and then test your prediction.
12. When you have finished the lab, return all materials to the locations specified by your instructor. Clean off the ink markings on the channel with isopropyl alcohol (or remove the colored stickers placed on the channel).

Analyze

1. **Interpret Data** Which color(s) of photons was able to remove at least one electron in your model?
2. **Interpret Data** Were any of the photons energetic enough to remove more than one electron? If so, identify the photon's color.
3. **Use Models** In step 9, what type of photon does the steel ball represent?
4. **Use Models** In step 10, what type of photon does the steel ball represent?
5. **Explain** Should photons of visible light be the only photons considered when investigating the photoelectric effect? Why or why not?
6. **Summarize** Summarize your observations in terms of the energies of photons.

Conclude and Apply

1. **Infer** What would happen if two red photons hit the two valence electrons at the same time? Test your prediction.
2. **Think Critically** Some materials hold on to their valence electrons more tightly than others. How could the model be modified to show this?
3. **Draw Conclusions** In this model, what happens to the photon's energy when it collides with an electron but does not remove the electron from the atom?

Going Further

Using the formula $E = hf$, where h is Planck's constant and f is the frequency of the electromagnetic radiation, calculate the energy of a red photon compared to the energy of a blue photon.

Real-World Physics

Photographers often have red lights in their darkrooms. Why do they use red light, but not blue light?

Physics Online

To find out more about the photoelectric effect and quantum theory, visit the Web site: **physicspp.com**

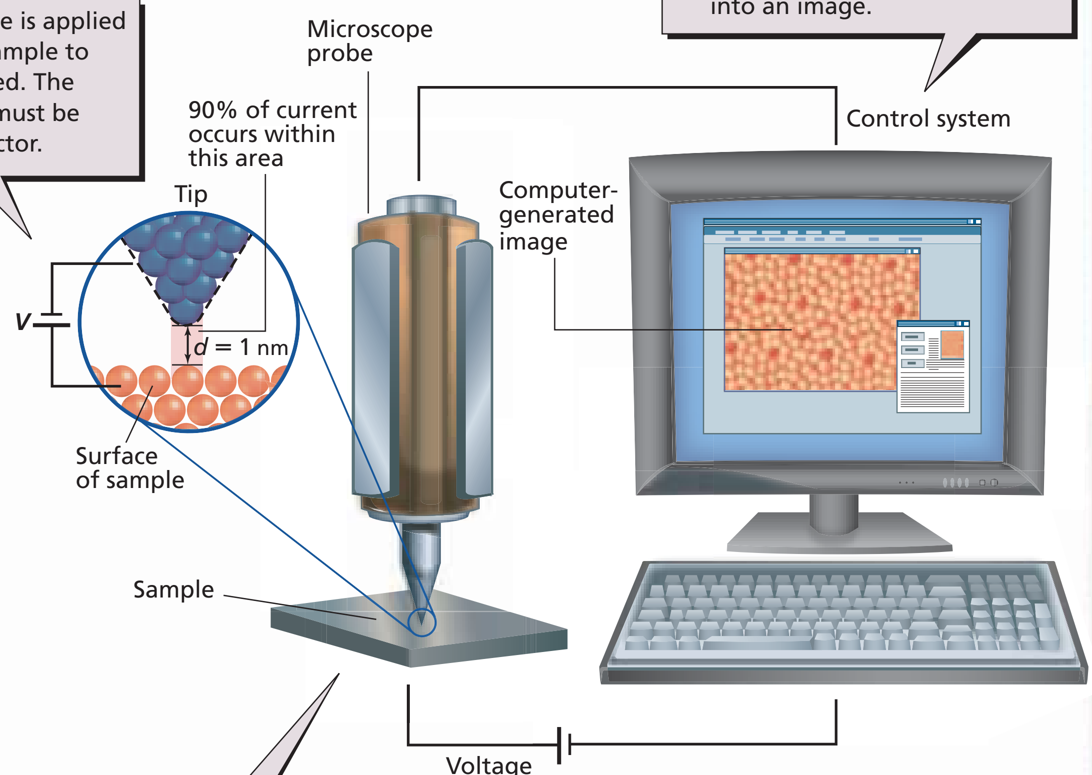
HOW it WORKS

Scanning Tunneling Microscope

The scanning tunneling microscope (STM) was invented in 1981 by Gerd Binnig and Heinrich Rohrer. Five years later, they were awarded the Nobel Prize in physics. The atomic-level resolution of an STM allows scientists to form images of atoms, such as the image of silicon atoms shown on the monitor below. How does an STM work?

3 The control system scans the probe back and forth and up and down above the surface of the sample. The distance between the surface and the tip is kept constant, producing a constant current. The up-and-down movement of the tip is recorded and turned into an image.

1 A voltage is applied to the sample to be viewed. The sample must be a conductor.



2 The tip of an STM's microscope probe is positioned extremely close to the sample (about 1 nm above the surface). As predicted by quantum physics, some electrons jump, or tunnel, between the surface of the sample and the tip of the probe. The moving electrons produce a current (measured in nanoamperes).

Thinking Critically

1. **Calculate** If the tunneling electron current is 1.0×10^{-9} A, how many electrons flow to the tip in 1 s?
2. **Evaluate** In an STM, the relationship between the current, I, and the distance, d, between the probe and the sample is $I = I_0 e^{-kd}$, where I_0 and k are constants. Use sample values to verify that the current decreases when the distance increases.
3. **Design an Experiment** What would you do if you wanted to use an STM to study a nonconductive sample?

Chapter 27 Study Guide

27.1 A Particle Model of Waves

Vocabulary

- emission spectrum (p. 724)
- quantized (p. 725)
- photoelectric effect (p. 726)
- threshold frequency (p. 726)
- photon (p. 727)
- work function (p. 731)
- Compton effect (p. 733)

Key Concepts

- Objects that are hot enough to be incandescent emit light because of the vibrations of the charged particles inside their atoms.
- The spectrum of incandescent objects covers a broad range of wavelengths. The spectrum depends upon the temperature of the incandescent objects.
- Planck explained the spectrum of an incandescent object by supposing that a particle can have only certain energies that are multiples of a constant, now called Planck's constant.

$$E = nhf$$

- Einstein explained the photoelectric effect by postulating that light exists in bundles of energy called photons.

$$E = hf = \frac{hc}{\lambda} = \frac{1240\ \text{eV·nm}}{\lambda}$$

- The photoelectric effect is the emission of electrons by certain metals when they are exposed to electromagnetic radiation.

$$KE = hf - hf_0$$

- The photoelectric effect allows the measurement of Planck's constant, h.
- The work function, which is equivalent to the binding energy of the electron, is measured by the threshold frequency in the photoelectric effect.
- The Compton effect demonstrates that photons have momentum, as predicted by Einstein.

$$p = \frac{hf}{c} = \frac{h}{\lambda}$$

- Even though photons, which travel at the speed of light, have zero mass, they do have energy and momentum.

27.2 Matter Waves

Vocabulary

- de Broglie wavelength (p. 735)
- Heisenberg uncertainty principle (p. 737)

Key Concepts

- The wave nature of material particles was suggested by de Broglie and verified experimentally by the diffraction of electrons through crystals. All moving particles have a wavelength, known as the de Broglie wavelength.

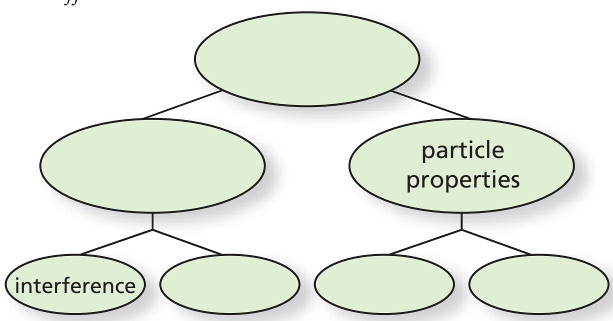
$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

- The particle and wave aspects are complementary parts of the complete nature of both matter and light.
- The Heisenberg uncertainty principle states that it is not possible to simultaneously measure the precise position and momentum of any particle of light or matter.

Chapter 27 Assessment

Concept Mapping

29. Complete the following concept map using these terms: *dual nature, mass, wave properties, momentum, diffraction.*



Mastering Concepts

30. **Incandescent Light** An incandescent lightbulb is controlled by a dimmer. What happens to the color of the light given off by the bulb as the dimmer control is turned down? (27.1)

31. Explain the concept of quantized energy. (27.1)

32. What is quantized in Max Planck's interpretation of the radiation of incandescent bodies? (27.1)

33. What is a quantum of light called? (27.1)

34. Light above the threshold frequency shines on the metal cathode in a photocell. How does Einstein's photoelectric effect theory explain the fact that as the light intensity increases, the current of photoelectrons increases? (27.1)

35. Explain how Einstein's theory accounts for the fact that light below the threshold frequency of a metal produces no photoelectrons, regardless of the intensity of the light. (27.1)

36. **Photographic Film** Because certain types of black-and-white film are not sensitive to red light, they can be developed in a darkroom that is illuminated by red light. Explain this on the basis of the photon theory of light. (27.1)

37. How does the Compton effect demonstrate that photons have momentum as well as energy? (27.1)

38. The momentum, p, of a particle of matter is given by $p = mv$. Can you calculate the momentum of a photon using the same equation? Explain. (27.2)

39. Explain how each of the following electron properties could be measured. (27.2)
a. charge **b.** mass **c.** wavelength

40. Explain how each of the following photon properties could be measured. (27.2)
a. energy **b.** momentum **c.** wavelength

Applying Concepts

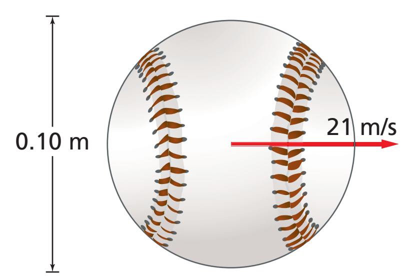
41. Use the emission spectrum of an incandescent body at three different temperatures shown in Figure 27-1 on page 724 to answer the following questions.
a. At what frequency does the peak emission intensity occur for each of the three temperatures?
b. What can you conclude about the relationship between the frequency of peak radiation emission intensity and temperature for an incandescent body?
c. By what factor does the intensity of the red light given off change as the body's temperature increases from 4000 K to 8000 K?

42. Two iron bars are held in a fire. One glows dark red, while the other glows bright orange.
a. Which bar is hotter?
b. Which bar is radiating more energy?

43. Will high-frequency light eject a greater number of electrons from a photosensitive surface than low-frequency light, assuming that both frequencies are above the threshold frequency?

44. Potassium emits photoelectrons when struck by blue light, whereas tungsten emits photoelectrons when struck by ultraviolet radiation.
a. Which metal has a higher threshold frequency?
b. Which metal has a larger work function?

45. Compare the de Broglie wavelength of the baseball shown in **Figure 27-11** with the diameter of the baseball.



■ **Figure 27-11**

Mastering Problems

27.1 A Particle Model of Waves

46. According to Planck's theory, how does the frequency of vibration of an atom change if it gives off 5.44×10^{-19} J while changing its value of n by 1?

47. What potential difference is needed to stop electrons with a maximum kinetic energy of 4.8×10^{-19} J?

48. What is the momentum of a photon of violet light that has a wavelength of 4.0×10^{2} nm?

49. The stopping potential of a certain metal is shown in **Figure 27-12.** What is the maximum kinetic energy of the photoelectrons in the following units?
a. electron volts **b.** joules

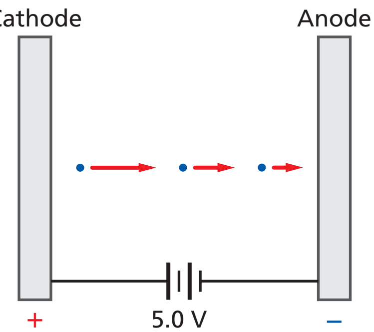


Figure 27-12

50. The threshold frequency of a certain metal is 3.00×10^{14} Hz. What is the maximum kinetic energy of an ejected photoelectron if the metal is illuminated by light with a wavelength of 6.50×10^{2} nm?

51. The threshold frequency of sodium is 4.4×10^{14} Hz. How much work must be done to free an electron from the surface of sodium?

52. If light with a frequency of 1.00×10^{15} Hz falls on the sodium in the previous problem, what is the maximum kinetic energy of the photoelectrons?

53. **Light Meter** A photographer's light meter uses a photocell to measure the light falling on the subject to be photographed. What should be the work function of the cathode if the photocell is to be sensitive to red light ($\lambda = 680$ nm) as well as to the other colors of light?

54. **Solar Energy** A home uses about 4×10^{11} J of energy each year. In many parts of the United States, there are about 3000 h of sunlight each year.
a. How much energy from the Sun falls on one square meter each year?
b. If this solar energy can be converted to useful energy with an efficiency of 20 percent, how large an area of converters would produce the energy needed by the home?

27.2 Matter Waves

55. What is the de Broglie wavelength of an electron moving at 3.0×10^{6} m/s?

56. What velocity would an electron need to have a de Broglie wavelength of 3.0×10^{-10} m?

57. A cathode-ray tube accelerates an electron from rest across a potential difference of 5.0×10^{3} V.
a. What is the velocity of the electron?
b. What is the wavelength associated with the electron?

58. A neutron is held in a trap with a kinetic energy of only 0.025 eV.
a. What is the velocity of the neutron?
b. Find the de Broglie wavelength of the neutron.

59. The kinetic energy of a hydrogen atom's electron is 13.65 eV.
a. Find the velocity of the electron.
b. Calculate the electron's de Broglie wavelength.
c. Given that a hydrogen atom's radius is 0.519 nm, calculate the circumference of a hydrogen atom and compare it with the de Broglie wavelength for the atom's electron.

60. An electron has a de Broglie wavelength of 0.18 nm.
a. How large a potential difference did it experience if it started from rest?
b. If a proton has a de Broglie wavelength of 0.18 nm, how large is the potential difference that it experienced if it started from rest?

Mixed Review

61. What is the maximum kinetic energy of photoelectrons ejected from a metal that has a stopping potential of 3.8 V?

62. The threshold frequency of a certain metal is 8.0×10^{14} Hz. What is the work function of the metal?

63. If light with a frequency of 1.6×10^{15} Hz falls on the metal in the previous problem, what is the maximum kinetic energy of the photoelectrons?

64. Find the de Broglie wavelength of a deuteron (nucleus of ^{2}H isotope) of mass 3.3×10^{-27} kg that moves with a speed of 2.5×10^{4} m/s.

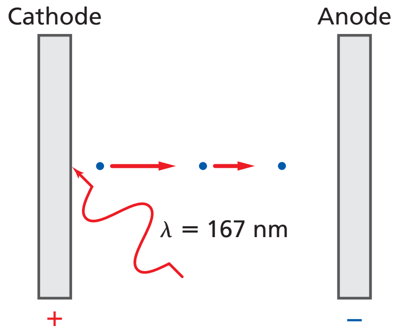
65. The work function of iron is 4.7 eV.
a. What is the threshold wavelength of iron?
b. Iron is exposed to radiation of wavelength 150 nm. What is the maximum kinetic energy of the ejected electrons in eV?

66. Barium has a work function of 2.48 eV. What is the longest wavelength of light that will cause electrons to be emitted from barium?

67. An electron has a de Broglie wavelength of 400.0 nm, the shortest wavelength of visible light.
a. Find the velocity of the electron.
b. Calculate the energy of the electron in eV.

68. **Electron Microscope** An electron microscope is useful because the de Broglie wavelengths of electrons can be made smaller than the wavelength of visible light. What energy in eV has to be given to an electron for it to have a de Broglie wavelength of 20.0 nm?

69. Incident radiation falls on tin, as shown in **Figure 27-13.** The threshold frequency of tin is 1.2×10^{15} Hz.
a. What is the threshold wavelength of tin?
b. What is the work function of tin?
c. The incident electromagnetic radiation has a wavelength of 167 nm. What is the kinetic energy of the ejected electrons in eV?

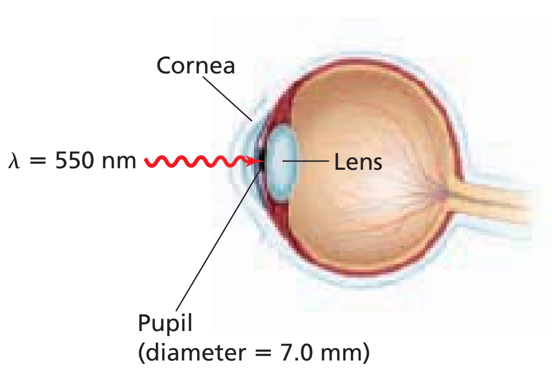


■ **Figure 27-13**

Thinking Critically

70. Apply Concepts A helium-neon laser emits photons with a wavelength of 632.8 nm.
a. Find the energy, in joules, of each photon emitted by the laser.
b. A typical small laser has a power of 0.5 mW (equivalent to 5×10^{-4} J/s). How many photons are emitted each second by the laser?

71. Apply Concepts Just barely visible light with an intensity of 1.5×10^{-11} W/m^2 enters a person's eye, as shown in **Figure 27-14.**
a. If this light shines into the person's eye and passes through the person's pupil, what is the power, in watts, that enters the person's eye?
b. Use the given wavelength of the incident light and information provided in Figure 27-14 to calculate the number of photons per second entering the eye.



■ **Figure 27-14**

72. Make and Use Graphs A student completed a photoelectric-effect experiment and recorded the stopping potential as a function of wavelength, as shown in **Table 27-1.** The photocell had a sodium cathode. Plot the data (stopping potential versus frequency) and use your calculator to draw the best-fit straight line (regression line). From the slope and intercept of the line, find the work function, the threshold wavelength, and the value of h/q from this experiment. Compare the value of h/q to the accepted value.

Table 27-1
Stopping Potential v. Wavelength

λ (nm)	V_0 (eV)
200	4.20
300	2.06
400	1.05
500	0.41
600	0.03

Writing in Physics

73. Research the most massive particle for which interference effects have been seen. Describe the experiment and how the interference was created.

Cumulative Review

74. The spring in a pogo stick is compressed 15 cm when a child who weighs 400.0 N stands on it. What is the spring constant of the spring? (Chapter 14)

75. A marching band sounds flat as it plays on a very cold day. Why? (Chapter 15)

76. A charge of 8.0×10^{-7} C experiences a force of 9.0 N when placed 0.02 m from a second charge. What is the magnitude of the second charge? (Chapter 20)

77. A homeowner buys a dozen identical 120-V light sets. Each light set has 24 bulbs connected in series, and the resistance of each bulb is 6.0 Ω. Calculate the total load in amperes if the homeowner operates all the sets from a single exterior outlet. (Chapter 23)

78. The force on a 1.2-m wire is 1.1×10^{-3} N. The wire is perpendicular to Earth's magnetic field. How much current is in the wire? (Chapter 24)

 For more problems, go to Additional Problems, Appendix B.

Standardized Test Practice

Multiple Choice

1. The energy level of an atom changes as it absorbs and emits energy. Which of the following is NOT a possible energy level of an atom?

- (A) $\frac{3}{4}hf$
- (B) hf
- (C) $3hf$
- (D) $4hf$

2. How is the threshold frequency related to the photoelectric effect?

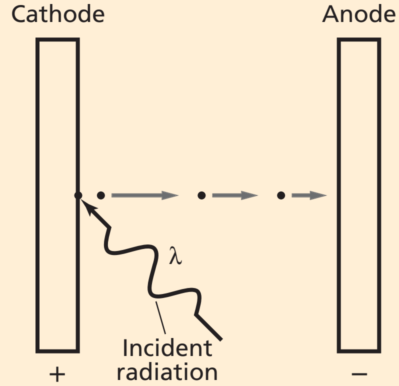
- (A) It is the minimum frequency of incident radiation needed to cause the ejection of atoms from the anode of a photocell.
- (B) It is the maximum frequency of incident radiation needed to cause the ejection of atoms from the anode of a photocell.
- (C) It is the frequency of incident radiation below which electrons will be ejected from an atom.
- (D) It is the minimum frequency of incident radiation needed to cause the ejection of electrons from an atom.

3. A photon has a frequency of 1.14×10^{15} Hz. What is the energy of the photon?

- (A) 5.82×10^{-49} J
- (B) 7.55×10^{-19} J
- (C) 8.77×10^{-16} J
- (D) 1.09×10^{-12} J

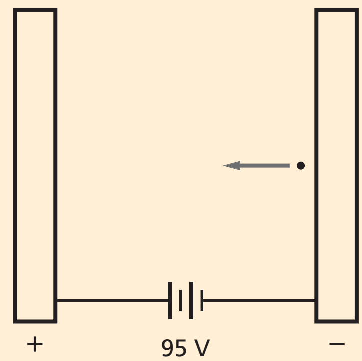
4. Radiation with an energy of 5.17 eV strikes a photocell as shown below. If the work function of the photocell is 2.31 eV, what is the energy of the ejected photoelectron?

- (A) 0.00 eV
- (B) 2.23 eV
- (C) 2.86 eV
- (D) 7.48 eV



5. As shown in the diagram below, an electron is accelerated by a potential difference of 95.0 V. What is the de Broglie wavelength of the electron?

- (A) 5.02×10^{-22} m
- (B) 1.26×10^{-10} m
- (C) 2.52×10^{-10} m
- (D) 5.10×10^{6} m



6. What is the de Broglie wavelength of an electron moving at 391 km/s? The mass of an electron is 9.11×10^{-31} kg.

- (A) 3.5×10^{-25} m
- (B) 4.79×10^{-15} m
- (C) 4.8×10^{-15} m
- (D) 1.86×10^{-9} m

7. What is the work function of a metal?

- (A) a measure of how much work an electron emitted from the metal can do
- (B) equal to the threshold frequency
- (C) the energy needed to free the metal atom's innermost electron
- (D) the energy needed to free the most weakly bound electron

Extended Answer

8. An object has a de Broglie wavelength of 2.3×10^{-34} m when its velocity is 45 m/s. What is the mass, in kg, of the object?

✓ Test-Taking TIP

Wear A Watch

If you are taking a timed test, make sure to pace yourself. Do not spend too much time on any one question. Skip over difficult questions and return to them after answering the easier questions.