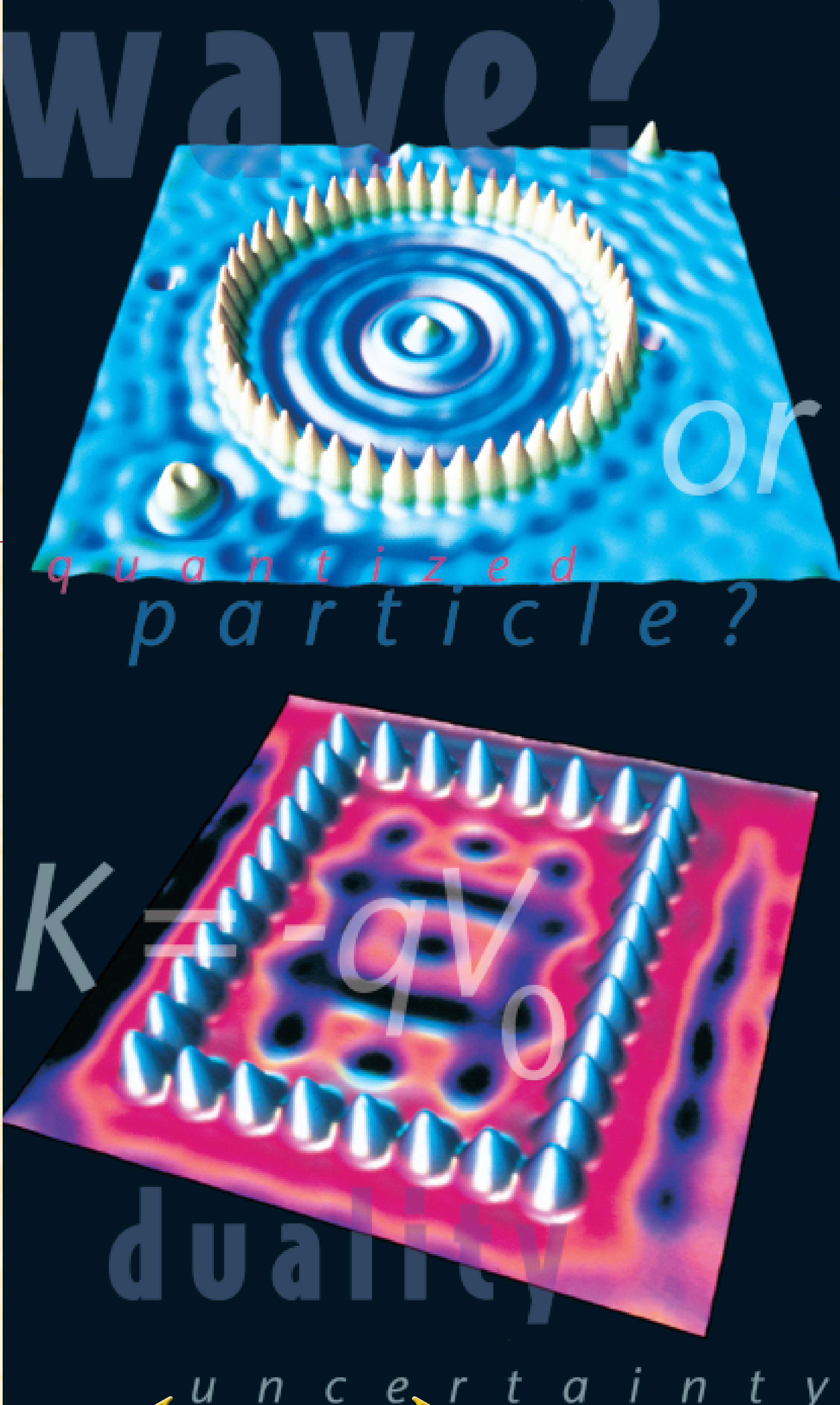
Electron Corral

Look at these extraordinary images. Would you believe that they are corrals for electrons? The peaks are individual iron atoms that IBM scientists placed, one by one, on a copper surface using a scanning tunneling microscope (STM). How does quantum theory permit the STM to work?

➥ *Look at the text on page 639 for the answer.*



CHAPTER

27 Quantum Theory

The startling ideas of quantum theory are the basis for the amazing scanning and tunneling microscope (STM). The first STM-produced image was that of the surface of gold. Displayed on a television monitor, the image included rows of precisely spaced atoms and wide terraces separated by steps merely one atom in height. In recognition of the important contribution this instrument made to the study of matter at the atomic level, the 1986 Nobel prize in physics was awarded to Gerd Binnig and Heinrich Roher, the inventors of the STM.

The STM allows scientists to penetrate deeply into the world of atoms and to manipulate matter in ways that were inconceivable only a short time ago. The STM and its cousins can produce pictures of the surfaces of metals, insulators, and other materials, including strands of DNA. STM images can be used to study friction on an atomic scale and to create new materials. The images can even be used to assemble "designer" molecules one atom at a time.

The basis of the STM can be explained by quantum theory, but the STM is not the only phenomenon with roots in quantum theory. Although the theory explains particle behavior at the microscopic level, the effects of the theory can be directly observable. Familiar quantum effects include the bright lights of neon signs, the particular hues of chemical flame tests, and the colors of brilliant fireworks displays. As you study this chapter, you'll learn more about the wave and particle nature of light and matter. Also, you'll be able to identify many other ways in which quantum ideas play a part in your everyday life.

WHAT YOU'LL LEARN

- You will describe light as a discrete, or quantized, bundle of momentum and energy.
- You will recognize that atom-sized particles of matter behave like waves, showing diffraction and interference effects.

WHY IT'S IMPORTANT

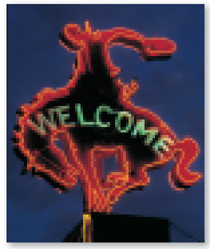
- Microwave ovens, lasers, televisions, computer monitors, and home security systems are a few of the many devices that depend upon the quantum nature of light and matter.

PHYSICS Online

To find out more about the duality of waves and particles, visit the Glencoe Science Web site at science.glencoe.com

CLICK HERE

27.1 Waves Behave Like Particles



OBJECTIVES

- **Describe** the spectrum emitted by a hot body and **explain** the basic theory that underlies the emission of hot-body radiation.
- **Explain** the photoelectric effect and **recognize** that quantum theory can explain it, whereas the wave theory cannot.
- **Explain** the Compton effect and **describe** it in terms of the momentum and energy of the photon.
- **Describe** experiments that demonstrate the particle-like properties of electromagnetic radiation.

In 1889, the experiments of Heinrich Hertz confirmed the predictions of Maxwell's theory, which you learned about in Chapter 26. All of optics seemed to be explainable in terms of electromagnetic theory. Only two small problems remained. Wave theory could not describe the spectrum of light emitted by a hot body such as molten steel or an incandescent lightbulb. Also, as discovered by Hertz himself, ultraviolet light discharged electrically charged metal plates. This effect, called the photoelectric effect, could not be explained by Maxwell's wave theory.

Radiation from Incandescent Bodies

Why was radiation from hot bodies a puzzle? Hot bodies contain vibrating particles, which radiate electromagnetic waves. Maxwell's theory should have had no conflict with this, but its prediction was wrong. Why? What radiation do hot bodies emit?

If you look through a prism at the light coming from an incandescent lightbulb, you will see all the colors of the rainbow. The bulb also emits infrared radiation, that you cannot see. **Figure 27–1** shows the spectra of incandescent bodies at three different temperatures: 4000 K, 5800 K, and 8000 K. A spectrum is a plot of the intensity of radiation emitted at various frequencies. Light and infrared radiation are produced by the vibration of the charged particles within the atoms of a body that is so hot it glows, or is incandescent. The shapes of the curves in **Figure 27–1** show that energy is emitted at a variety of frequencies that depend on temperature. At each temperature, there is a frequency at which the maximum amount of energy is emitted. By comparing the three curves, you can see that as the temperature increases, the frequency at which the maximum energy is emitted also increases.

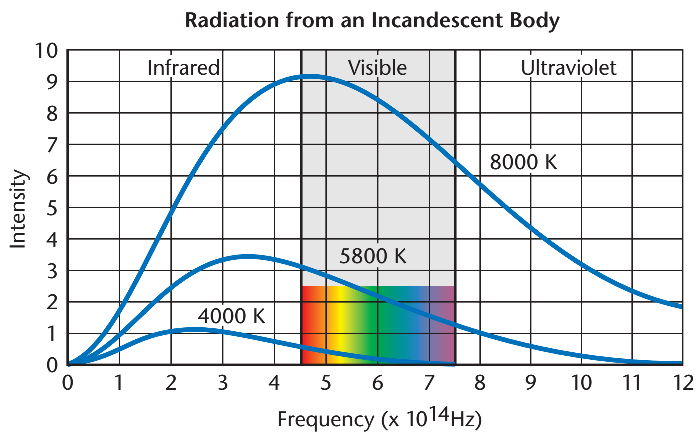


FIGURE 27–1 This graph shows the spectra of incandescent bodies at three temperatures.

Suppose you put a lightbulb on a dimmer control. You gradually turn up the voltage, increasing the temperature of the glowing filament. The color changes from deep red through orange to yellow and finally, to white. Because higher temperature results in radiation of higher frequency, more radiation at the higher-frequency end of the visible spectrum, the violet end, is produced and the body appears to be whiter. The colors you see depend upon the relative amounts of emission at various frequencies and the sensitivity of your eyes to those colors. Compare the position of the maximum of each curve in **Figure 27–1** with the visible spectrum.

The total power emitted also increases with temperature. The amount of energy emitted every second in electromagnetic waves is proportional to the temperature in kelvins raised to the fourth power, T^4. Thus, hotter sources radiate considerably more power than cooler bodies do. The sun, for example, is a dense ball of gases heated to incandescence by the energy produced within it. It has a surface temperature of 5800 K and a yellow color. The sun radiates 4×10^{26} W, an enormous amount of power. On average, every square meter on Earth's surface receives about 1000 J of energy each second.

Why does the spectrum have the shape shown in **Figure 27–1?** Maxwell's theory could not account for it. Between 1887 and 1900, many physicists tried to predict the shape of this spectrum using existing physical theories, but all failed. In 1900, the German physicist Max Planck (1858–1947), shown in **Figure 27–2,** found that he could calculate the spectrum only if he introduced a revolutionary hypothesis—that energy is not continuous. Planck assumed that the energy of vibration of the atoms in a solid could have only specific frequencies as shown by the following equation.

Energy of Vibration $E = nhf$

In the equation, f is the frequency of vibration of the atom, h is a constant, and n is an integer such as 0, 1, 2, or 3. The energy, E, could have the values hf, $2hf$, $3hf$, and so on, but never, for example, $2/3hf$. This behavior is described by saying that energy is **quantized.** Quantized energy comes only in packages of specific amounts.

Planck also proposed that atoms do not always radiate electromagnetic waves when they are vibrating, as predicted by Maxwell. Instead, he proposed that they emit radiation only when their vibration 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 was extremely small, about 7×10^{-34} J/Hz. 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 Planck himself. It was the first hint that the physics of Newton and Maxwell might be valid only under certain conditions.

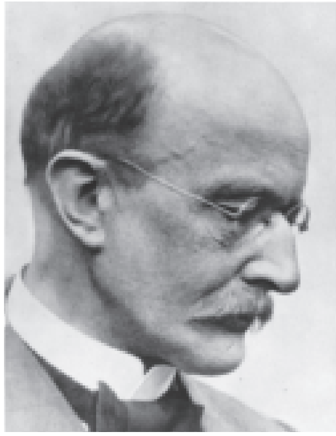


FIGURE 27–2 Max Planck (1858–1947) was awarded the Nobel prize in 1918 for his discovery of the quantized nature of energy.

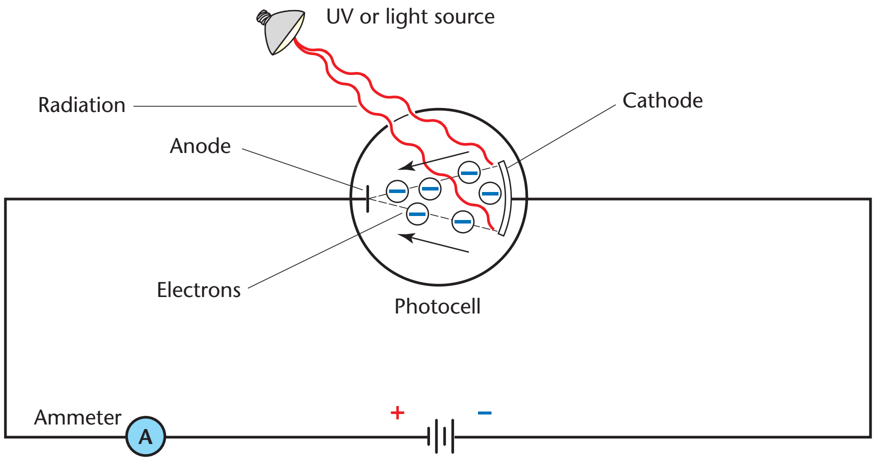
Pocket Lab

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. Describe the results. Repeat the experiment using a green filter. Explain the results. Would you expect the fluorescein to glow when a blue filter is used? Explain your prediction. Try it.

Analyze and Conclude Write a brief explanation of your observations.

FIGURE 27–3 Electrons ejected from the cathode flow to the anode and thus complete the circuit.



The Photoelectric Effect

There was a second troubling experimental result unexplained by Maxwell. A negatively charged zinc plate was discharged when ultraviolet radiation fell on it, but it remained charged when ordinary visible light fell on it. Both ultraviolet light and visible light are electromagnetic radiation, so why would the zinc plate be discharged by one and not by the other? And why is a positively charged zinc plate not similarly discharged? Further study showed that the negatively charged zinc plate was discharged by losing or emitting 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 like the one in **Figure 27–3.** The cell contains two metal electrodes sealed in an evacuated tube. The air has been removed to keep the metal surface clean and to keep electrons from being stopped by air molecules. The large electrode, the cathode, is usually coated with cesium or another alkali metal. The second electrode, the anode, is made of a thin wire so that it blocks only the smallest amount of radiation. The tube is often made of quartz to permit ultraviolet wavelengths to pass through. A potential difference that attracts electrons to the anode is placed across the electrodes.

When no radiation falls on the cathode, there is no current in the circuit. But when radiation does fall on the cathode, there is a current, as shown by the meter in **Figure 27–3.** The current results from the ejection of electrons from the cathode by the radiation. Hence, these electrons are called photoelectrons. The electrons travel to the anode, the positive electrode.

Not all radiation results in a current. Electrons are ejected only if the frequency of the radiation is above a certain minimum value, called the **threshold frequency,** f_0. The threshold frequency varies with the metal. All wavelengths of visible light except red will eject electrons from cesium, but no wavelength of visible light will eject electrons from zinc. Ultraviolet light is needed for zinc. Radiation of a frequency below f_0 does not eject any electrons from the metal, no matter how intense the light is. However, even if the incident light is very dim, radiation at or above the threshold frequency causes electrons to leave the metal immediately; the greater the intensity of the incident radiation, the larger the flow of photoelectrons.

The electromagnetic wave theory cannot explain all of these facts. According to the wave theory, it is the intensity of the radiation, not the frequency, that determines the strength of the electric and magnetic fields. A more intense radiation, regardless of frequency, has stronger electric and magnetic fields. According to wave theory, the electric field accelerates and ejects the electrons from the metal. With very faint light shining on the metal, electrons would need to absorb energy for a very long time before they gained enough to be ejected. But, as you have learned, electrons are ejected immediately even in dim light if the frequency of the radiation is at or above the threshold frequency.

In 1905, Albert Einstein published a revolutionary theory that explained the photoelectric effect. According to Einstein, light and other forms of radiation consist of discrete bundles of energy, which were later called **photons.** The energy of each photon depends on the frequency of the light. The energy is represented by the equation $E = hf$, where h is Planck's constant, 6.63×10^{-34} J/Hz. Because the unit Hz $= 1/\text{s}$ or s^{-1}, the unit of Planck's constant also can be expressed as J·s.

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

Einstein's photoelectric-effect theory explains the existence of a threshold frequency. A photon with a minimum energy, hf_0, is needed to eject an electron from the metal. If the photon has a frequency below f_0, the photon does not have the energy needed to eject an electron. Light with a frequency greater than f_0 has more energy than is needed to eject an electron. The excess energy, $hf - hf_0$, becomes the kinetic energy of the electron.

Kinetic Energy of an Electron $K = hf - hf_0$

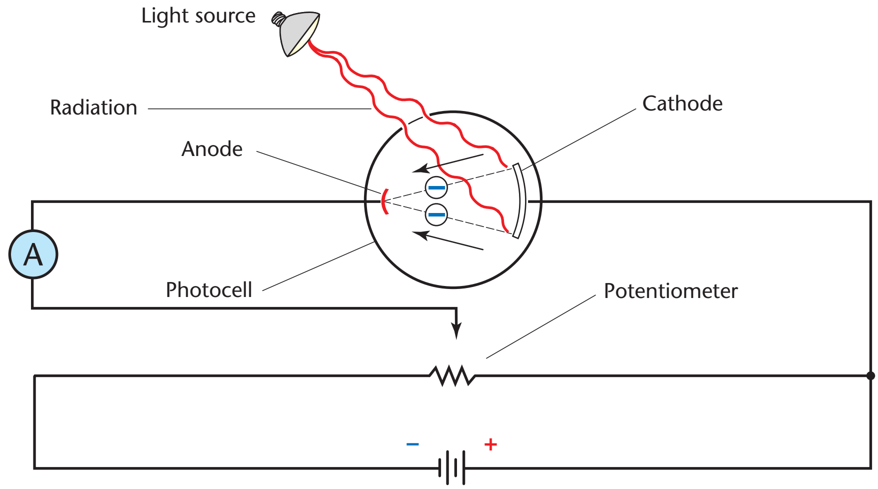
Einstein's equation is a statement of conservation of energy. The incoming photon has energy hf. An amount of energy, hf_0, is needed to free the electron from the metal. The remainder becomes the kinetic energy of the electron. Note that an electron cannot simply accumulate photons until it has enough energy; only one photon interacts with one electron. In addition, hf_0 is the minimum energy needed to free an electron. The minimum energy is the amount of energy needed to release

HELP WANTED

PARTICLE PHYSICIST

The successful candidate will analyze elementary particles (quarks, leptons, and bosons) and must be skilled in using accelerators to study these particles and their interactions. A knowledge of computers and specialized cameras is also required. Most positions in high-energy physics are in government or university research facilities and require a doctorate in physics or a master's degree and extensive experience. For more information, contact one of the following organizations at the same address.
American Institute of Physics or the American Physical Society
One Physics Ellipse
College Park, MD 20740.

FIGURE 27–4 The kinetic energy of the ejected electrons can be measured using this apparatus. An ammeter measures the current through the circuit.



the most loosely held electron in an atom. Because not all electrons in an atom have the same energy, some need more than this minimum to escape, and as a result, they will have differing kinetic energies. Thus, the expression *kinetic energy of the ejected electrons* refers to the maximum kinetic energy an ejected electron could have. Some electrons will have less kinetic energy.

How can Einstein's theory be tested? The kinetic energy of the ejected electrons can be measured indirectly by a device like the one pictured in **Figure 27–4.** A variable electric potential difference across the tube makes the anode negative. By analogy to gravity, the electrons must expend energy, in effect climb a hill, to reach the anode. Only if they have enough kinetic energy when they leave the cathode will they reach the anode before being turned back. Light of the chosen frequency illuminates the cathode. An ammeter measures the current flowing through the circuit. Gradually, the experimenter increases the opposing potential difference, making the anode more negative. As the opposing potential difference increases, more and more kinetic energy is needed for the electrons to reach the anode, and fewer and fewer electrons arrive there to complete the circuit. At some voltage, called the stopping potential, no electrons have enough kinetic energy to reach the anode, and the current falls to zero. The maximum kinetic energy, K, at the cathode equals the work done by the electric field in stopping them. That is, $K = -qV_0$. In the 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).

The joule is too large a unit of energy to use with atomic systems. A more convenient energy unit is the electron volt (eV). One electron volt is the energy of an electron accelerated across a potential difference of one volt.

$$1 \text{ eV} = (1.60 \times 10^{-19} \text{ C})(1 \text{ V}) = 1.60 \times 10^{-19} \text{ C·V}$$

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

Pocket Lab

See the Light

Close the shades and turn off all the lights in the room. Look at a 150-W lamp as you use a dimmer switch to slowly increase and decrease the voltage across the lamp. Describe what you observe. What would you expect to see if you repeated the experiment while looking through a diffraction grating? Why? Try it. Describe your results.

Analyze and Conclude Describe your observations.

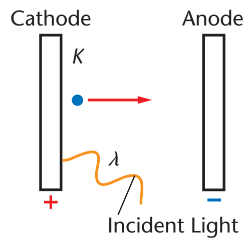
Example Problem

The Kinetic Energy of a Photoelectron

The stopping potential, V_0, that prevents electrons from flowing across 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 J and eV.

Sketch the Problem

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



Calculate Your Answer

Known:

$V_0 = 4.0$ V

$q = -1.60 \times 10^{-19}$ C

Unknown:

K (in J and eV) = ?

Strategy:

The electric field does work on the electrons. When the work done, W, equals the negative of the initial kinetic energy, K, electrons no longer flow across the photocell. Use V_0 to find the work done, which equals the kinetic energy.

Calculations:

$K + W = 0$; $K = -W$

$W = qV_0$, so $K = -qV_0$

$K = -(-1.60 \times 10^{-19}\ \text{C})(4.0\ \text{V})$

$= +6.4 \times 10^{-19}$ J

1 eV $= 1.60 \times 10^{-19}$ J

so $K = (6.4 \times 10^{-19}\ \text{J})(1\ \text{eV}/1.60 \times 10^{-19}\ \text{J})$

$= 4.0$ eV

Check Your Answer

- Are the units correct? 1 V = 1 J/C, so CV = J.
- Does the sign make sense? Kinetic energy is always positive.
- Is the magnitude realistic? Energy in electron volts is equal in magnitude to stopping potential difference in volts.

Problem Solving Strategies

A Useful Unit for *hc*.

The energy of a photon of wavelength λ is given by $E = hf$. But, $f = c/\lambda$, so $E = hc/\lambda$. Thus, it's helpful to know the value of hc in eV·nm so that when you divide by λ in nm, you obtain the energy in eV.

Convert the constant hc to the unit eV·nm as follows.

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

$= 1240$ eV·nm

Thus, $E = hc/\lambda = (1240\ \text{eV·nm})/\lambda$, where λ is in nm and E is in eV.

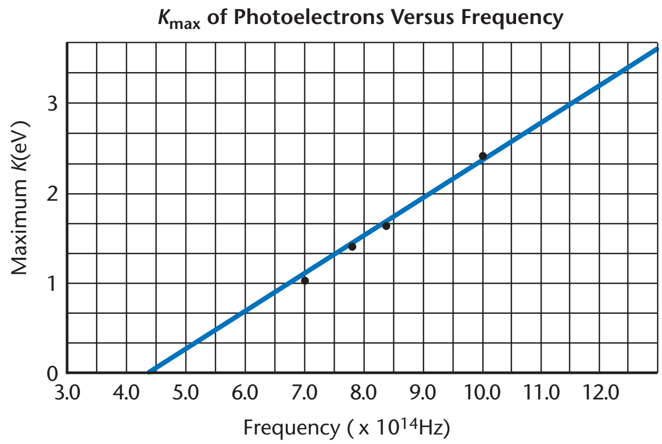


FIGURE 27–5 The graph shows that as the frequency of the incident radiation increases, the kinetic energy of the ejected electrons increases proportionally.

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 you can see in **Figure 27–5.** All metals have similar graphs with the same slope. The slope of all of the lines is Planck's constant, h.

$$h = \frac{\Delta K}{\Delta f} = \frac{\text{change in maximum kinetic energy of ejected electrons}}{\text{change in frequency of incident radiation}}$$

The graphs of various metals differ only in the threshold frequency that is needed to free electrons. In **Figure 27–5,** the threshold frequency, f_0, is the point at which $K = 0$. In this case, f_0, located at the intersection of the curve with the x-axis, is approximately 4.4×10^{14} Hz. The threshold frequency is related to the energy needed to free the most weakly bound electron from a metal. This is called the **work function** of the metal. The work function is thus measured by 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.

F.Y.I.

How are waves and particles alike? They both carry momentum and energy. Particles carry these quantities in their mass, waves in their fields.

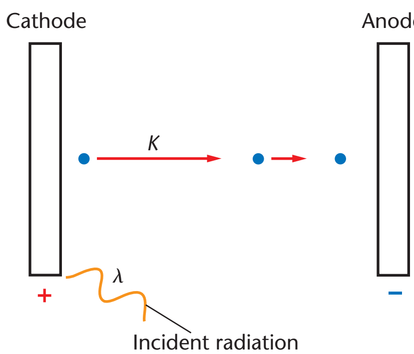
Example Problem

Finding the Energy of Photoelectrons

Sodium 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?



Sketch the Problem

- In your drawing, include the positive cathode and negative anode.

Calculate Your Answer

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

Strategy:	**Calculations:**
a. Find the work function using Planck's constant and the threshold wavelength.	$W = hf_0 = hc/\lambda_0$ $= (1240 \text{ eV·nm})/(536 \text{ nm})$ $= 2.31 \text{ eV}$
b. Use Einstein's photoelectric-effect equation to determine the energy of the ejected electron.	Photon energy $= hc/\lambda$ $= (1240 \text{ eV·nm})/(348 \text{ nm})$ $= 3.56 \text{ eV}$
Subtract the work function to find the kinetic energy of the electrons.	$K = hf - hf_0 = hc/\lambda - hc/\lambda_0$ $= 3.56 \text{ eV} - 2.31 \text{ eV}$ $= 1.25 \text{ eV}$

Check Your Answer

- Are the units correct? Performing algebra on the units verifies K in eV.
- Do the signs make sense? K should be positive.
- Are the magnitudes realistic? Energies should be a few electron volts.

Practice Problems

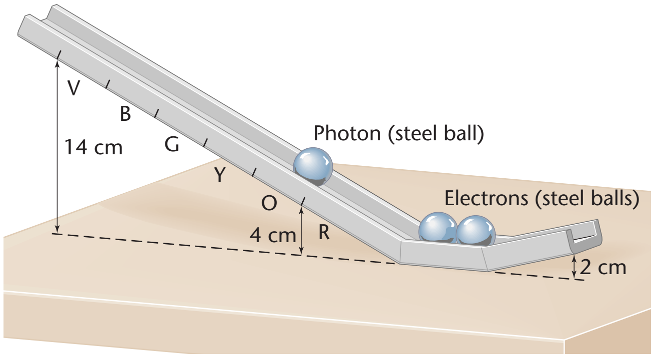
1. The stopping potential required to prevent current through a photocell is 3.2 V. Calculate the kinetic energy in joules of the photoelectrons as they are emitted.
2. The stopping potential for a photoelectric cell is 5.7 V. Calculate the kinetic energy of the emitted photoelectrons in eV.
3. The threshold wavelength of zinc is 310 nm.
   a. Find the threshold frequency of zinc.
   b. What is the work function in eV of zinc?
   c. Zinc in a photocell is irradiated by ultraviolet light of 240 nm wavelength. What is the kinetic energy of the photoelectrons in eV?
4. The work function for cesium is 1.96 eV.
   a. Find the threshold wavelength for cesium.
   b. What is the kinetic energy in eV of photoelectrons ejected when 425-nm violet light falls on the cesium?

Physics Lab

Red Hot or Not?

Problem

How well do steel balls simulate the photoelectric effect?



Materials

2-cm steel balls
grooved channel (U-channel or shelf bracket)
red, orange, yellow, green, blue, and violet marking pens or colored stickers

Procedure

1. Shape the grooved channel as shown in the diagram. Mark a point on the channel, 4 cm above the table, with R for red.
2. Mark a point on the channel, 14 cm above the table, with V for violet. Place marks for blue, green, yellow, and orange uniformly between R and V.
3. Place two steel balls at the lowest point on the channel. These steel balls represent valence electrons in the atom.
4. Place a steel ball on the channel at the red mark. This represents a photon of red light which has the lowest energy of the six colors of light being modeled.
5. Release the photon and see if the electrons are removed from the atom, that is, see if either steel ball escapes from the channel.
6. Remove the steel ball that represents the photon from the lower part of the channel.
7. Repeat steps 4–6 for each color's mark on the channel. **Note:** Always start with two electrons at the low point in the channel. Record your observations.
8. When you have completed the lab, dispose of or recycle appropriate materials. Put away materials that can be reused.

Data and Observations

1. Identify the photons by the color mark from which they were released. Which color of photons was able to remove the electrons?
2. Did one photon ever remove more than one electron? If so, what was its color?
3. Summarize your observations in terms of the energies of the photons.

Analyze and Conclude

1. **Making Predictions** Predict what would happen if two red photons could hit the electrons at the same time.
2. **Testing Predictions** Start two steel balls (photons) at the red mark on the channel and see what happens. Describe the results.
3. **Making Inferences** Some materials hold their valence electrons tighter than others. How could the model be modified to show this?

Apply

1. Photographers often have red lights in their darkrooms. Explain why they use red light but not blue light.

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 hf/c. Because $f/c = 1/\lambda$, the photon's momentum is represented by the following equation.

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

Experiments done by an American physicist, Arthur Holly Compton, in 1922 tested Einstein's theory. Compton directed X rays of known wavelength at a graphite target, as shown in **Figure 27–6a,** and measured the wavelengths of the X rays scattered by the target. He found that some of the X rays were scattered without change in wavelength. Other scattered X rays, however, had a longer wavelength than the original radiation, as shown in **Figure 27–6b.** The wavelength of the first maximum corresponds to the wavelength of the original incident X rays; the maximum at longer wavelength results from the scattered X rays.

Recall that the energy of a photon is hf, and that $f = c/\lambda$. Thus, the energy of the photon is expressed by the following equation.

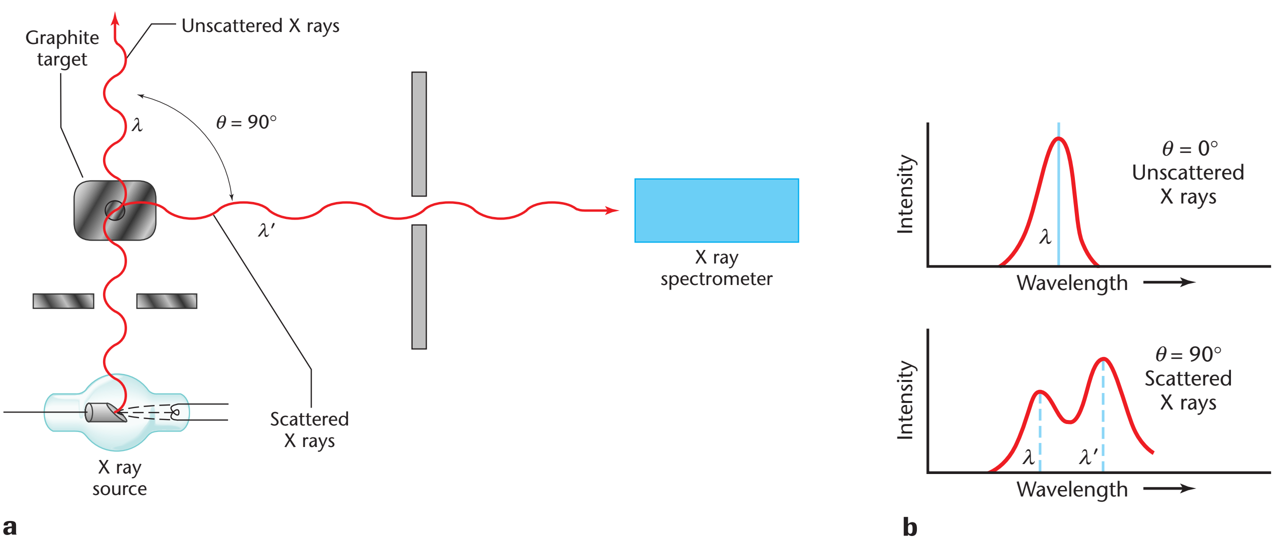
Photon Energy $$E = \frac{hc}{\lambda}$$

The equation tells you 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.** It is a tiny shift, about 10^{-3} nm, and so is measurable

F.Y.I.

A photovoltaic cell can act like an on-off switch. There is current in a circuit when light of a given frequency falls upon the photovoltaic cell. When the light beam is broken, the current ceases.

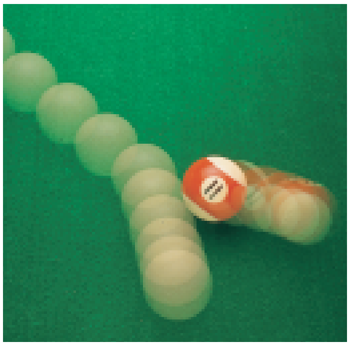
FIGURE 27–6 Compton used an apparatus similar to that shown in **(a)** to study the nature of photons. In **(b),** the increased wavelength of the scattered photons is evidence that the X-ray photons have lost energy.

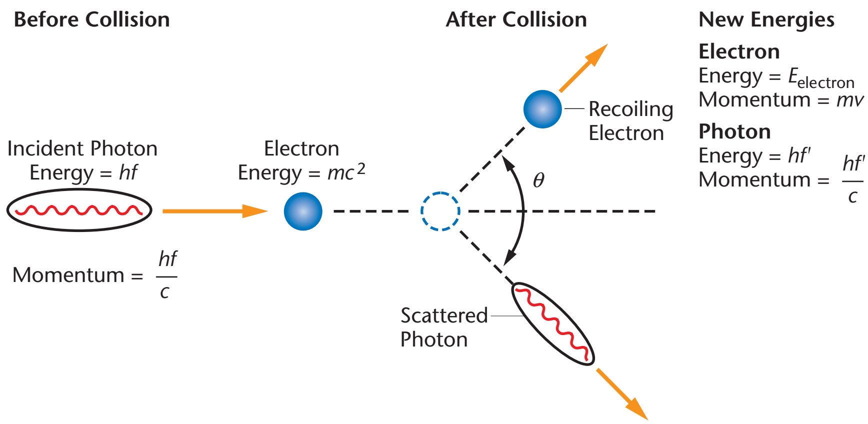


only when X rays having wavelengths of 10^{-2} nm or less are used. In later experiments, Compton observed that electrons were ejected from the graphite block during the experiment. He suggested that the X-ray photons collided with electrons in the graphite target and transferred energy and momentum. These collisions were similar to the elastic collisions experienced by the two billiard balls shown in **Figure 27–7.** Compton tested this suggestion by measuring the energy of the ejected electrons. He found that the energy and momentum gained by the electrons equal the energy and momentum lost by the photons. Photons obey the laws of conservation of momentum and energy.

Compton's experiments further verified Einstein's theory of photons. A photon is a particle that has energy and momentum. Unlike matter, however, a photon has no mass and travels at the speed of light.

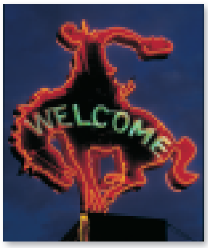
FIGURE 27–7 When a photon strikes an electron, the energy and momentum gained by the electron equal the energy and momentum lost by the photon.





27.1 Section Review

1. Research and describe the history of quantum physics. Include Planck's and Einstein's contributions.
2. As the temperature of a body is increased, how does the frequency of peak intensity change? How does the total energy radiated change?
3. An experimenter sends an X ray into a target. An electron, but no other radiation, comes out. Was the event the photoelectric or Compton effect? Describe the Compton effect and the photoelectric effect. How does the photoelectric effect demonstrate quantized energy?
4. **Critical Thinking** In the Compton effect, the collision of two billiard balls serves as a model for the interaction of a photon and an electron. Suppose the electron were replaced by the much more massive proton. Would the proton gain as much energy from the collision as the electron did? Would the photon lose as much energy as it did colliding with the electron?



Particles Behave Like Waves

27.2

The photoelectric effect and Compton scattering showed that an electromagnetic wave has the properties of a particle. If a wave behaves like a particle, could a particle behave like a wave? French physicist Louis-Victor de Broglie (1892–1987) suggested in 1923 that material particles do 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 and **solve** problems relating wavelength to particle momentum.
- **Recognize** the dual nature of both waves and particles and the importance of the Heisenberg uncertainty principle.

Matter Waves

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

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

If you solve this equation for wavelength, you will find that the **de Broglie wavelength** of the particle is represented by

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

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. However, in 1927, the results of two different experiments showed that electrons are diffracted just as light is. In one experiment, English physicist G. P. Thomson aimed a beam of electrons at a very thin crystal. The 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 27–8** shows the pattern made by diffracting electrons. The two experiments proved that material particles have wave properties.

The wave nature of objects of ordinary size is not observable because the wavelengths are extremely short. Consider the de Broglie wavelength of a 0.25-kg baseball when it leaves a bat with a speed of 21 m/s.

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}\ \text{J}\cdot\text{s}}{(0.25\ \text{kg})(21\ \text{m/s})} = 1.3 \times 10^{-34}\ \text{m}$$

The wavelength is far too small to have observable effects. However, you will see in the following example problem that an object as small as an electron has a wavelength that can be observed and measured.

Picture not available on CD

FIGURE 27–8 Electron diffraction patterns, such as this one for which a cubic zirconium crystal was used, demonstrate the wave properties of particles.

Example Problem

The de Broglie Wavelength of an Electron

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

Calculate Your Answer

Known:

$V = 75\ \text{V}$

$q = 1.60 \times 10^{-19}\ \text{C}$

$m = 9.11 \times 10^{-31}\ \text{kg}$

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

Unknown:

λ (de Broglie) $= ?$

Strategy:

Use the kinetic energy provided by the acceleration across a potential difference to find velocity.

Calculations:

$K = qV$, so $1/2mv^2 = qV$

$$v = \sqrt{\frac{2qV}{m}} = \sqrt{\frac{2(1.60 \times 10^{-19}\ \text{C})(75\ \text{V})}{9.11 \times 10^{-31}\ \text{kg}}} = 5.1 \times 10^{6}\ \text{m/s}$$

Find p.

$$p = mv = (9.11 \times 10^{-31}\ \text{kg})(5.1 \times 10^{6}\ \text{m/s}) = 4.6 \times 10^{-24}\ \text{kg·m/s}$$

Use p to find the de Broglie wavelength.

$$\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}\ \text{J·s}}{4.6 \times 10^{-24}\ \text{kg·m/s}} = 1.4 \times 10^{-10}\ \text{m} = 0.14\ \text{nm}$$

Check Your Answer

- Are the units correct? Performing algebra 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? λ is close to 0.1 nanometer, the spacing between the atoms in a solid.

Practice Problems

5. An electron is accelerated by a potential difference of 250 V.
   a. What is the speed of the electron?
   b. What is the de Broglie wavelength of this electron?

6. 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?

7. An X ray with a wavelength 5.0×10^{-12} m is traveling in a vacuum.
   a. Calculate the momentum associated with this X ray.
   b. Why does the X ray exhibit little particle behavior?

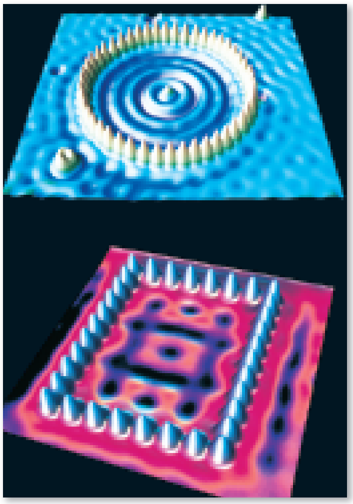
Particles and Waves

When you think of a particle, you think of mass, size, kinetic energy, and momentum. The properties of a wave, on the other hand, are frequency, wavelength, and amplitude. Is light a particle or a wave? Many physicists and philosophers have tried to work out an answer to this question. Most share a belief that the particle and wave aspects of light show complementary views of the true nature of light and must be taken together. Either model alone is incomplete.

How does quantum theory permit the scanning tunneling microscope to work? The STM works because electrons behave not only like particles, but also like waves. An STM has a fine needle-like tip positioned only a few nanometers above the surface to be studied. A potential difference is applied between the tip and surface. Because the tip and surface do not touch, you might think there would be no current. But electrons, acting like waves, can "tunnel" through the electric potential barrier created by the gap. The tiny current they create is very sensitive to the width of the gap. As the needle moves across the surface, the size of the current changes as the height of the surface changes. A computer creates an image of the shape of the surface.

Electron Corral

Answers question from page 624.



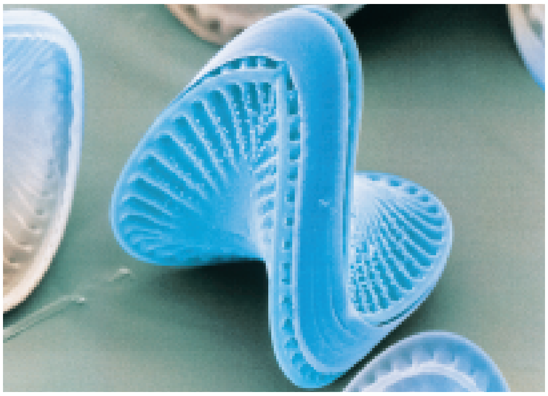
Physics & Technology

Say “Cheese”!

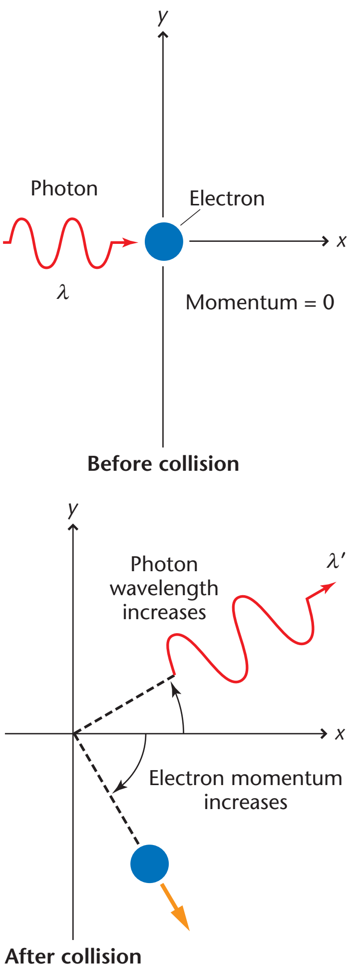
Look carefully at the photograph. Could you guess that this creature is a diatom that normally inhabits ocean waters? This breathtaking picture was taken by an electron microscope, a device that uses lenses, an electron beam, and often a computer to produce amazingly detailed images of objects that are as small as a few tenths of a nanometer.

A transmission electron microscope (TEM) uses electrons, electromagnetic lenses, and a vacuum to produce images that vary in contrast depending upon the heavy-metal stains used in specimen preparation. These metals prevent the electron beam from penetrating certain areas of the specimen while allowing electrons to flow freely through other sections, thereby creating contrast.

A scanning electron microscope, SEM, is identical to a TEM except that an SEM contains a deflection coil. This enables the electron beam to sweep across the sample and produce an image of electrons reflected from it.



Thinking Critically Like the SEM, the scanning transmission electron microscope, (STEM), contains a deflection coil. What advantages might the STEM have over either of its counterparts for the viewing of biological specimens?



Determining location and momentum Many physicists hold that the properties of an object can be defined only by devising an experiment that can measure them. One cannot simply say that a particle is at a certain location moving with a specific speed. Rather, an experiment must be described that will locate the particle and measure its speed.

How can you find the location of a particle? You must touch it or reflect light from it, as illustrated in **Figure 27-9**. Then the reflected light must be collected by an instrument or the human eye. Because of diffraction effects, light spreads out, making it impossible to locate the particle exactly. The spreading can be reduced by decreasing the wavelength of the light; the shorter the wavelength, the more precisely the location can be measured.

The Compton effect, however, means that when light of short wavelengths (high energy) strikes a particle, the momentum of the particle is changed. Therefore, the act of precisely measuring the location of a particle has the effect of changing the particle's momentum. The more precise the effort to measure the particle's location, the larger the likely change in its momentum.

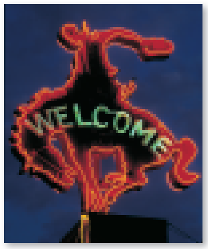
In the same way, if the momentum of the particle is measured, the position of the particle changes. The conclusion is that it is impossible to measure precisely both the position and momentum of a particle at the same time. This fact is called the **Heisenberg uncertainty principle,** named for German physicist Werner Heisenberg. It is the result of the dual wave and particle description of light and matter.

FIGURE 27–9 A particle can be seen only when light is scattered from it, but the scattering changes the momentum of the electron.

27.2 Section Review

1. If you want to increase the wavelength of a proton, you slow it down. What could you do to increase the wavelength of a photon?
2. If you try to find the location of a beam of light by having it pass through a narrow hole, why can you not tell much about the direction of the beam?
3. Review the dual nature of matter. Analyze and critique the wave nature and particle nature of electrons.
4. **Critical Thinking** Physicists recently made a diffraction grating of standing waves of light. They sent atoms through this grating and observed interference. If the spacing of the slits in the grating were half a wavelength, 250 nm, roughly what would you expect that the de Broglie wavelength of the atoms should be?

CHAPTER 27 REVIEW



Summary

Key Terms

27.1
- quantized
- photoelectric effect
- threshold frequency
- photon
- work function
- Compton effect

27.2
- de Broglie wavelength
- Heisenberg uncertainty principle

27.1 Waves Behave Like Particles

- Objects 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.
- The photoelectric effect is the emission of electrons by certain metals when they are exposed to electromagnetic radiation.
- Einstein explained the photoelectric effect by postulating that light comes in bundles of energy called photons.
- The photoelectric effect allows the measurement of Planck's constant, h.
- The work function, the energy with which electrons are held inside metals, is measured by the threshold frequency in the photoelectric effect.
- The Compton effect demonstrates the momentum of photons, first predicted by Einstein.
- Photons, or light quanta, are massless and travel at the speed of light. Yet they have energy, hf, and momentum, $p = h/\lambda$.

27.2 Particles Behave Like Waves

- The wave nature of material particles was suggested by de Broglie and verified experimentally by diffracting electrons off crystals.
- 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 measure precisely the position and momentum of a particle (light or matter) at the same time.

Key Equations

27.1

$E = nhf \qquad E = hf = \dfrac{hc}{\lambda} \qquad K = hf - hf_0 \qquad p = \dfrac{hf}{c} = \dfrac{h}{\lambda}$

27.2

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

Reviewing Concepts

Section 27.1

1. Explain the concept of quantized energy.
2. In Max Planck's interpretation of the radiation of incandescent bodies, what is quantized?
3. What is a quantum of light called?
4. Light above the threshold frequency shines on the metal cathode in a photocell. How does Einstein's theory explain the fact that as the light intensity is increased, the current of photoelectrons increases?
5. 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.

6. Certain types of black-and-white film are not sensitive to red light; they can be developed with a red safelight on. Explain this on the basis of the photon theory of light.
7. How does the Compton effect demonstrate that photons have momentum as well as energy?

Section 27.2

8. The momentum of a material particle is *mv*. Can you calculate the momentum of a photon using *mv*? Explain.
9. Describe how the following properties of the electron could be measured. Explain in each case what is to be done.
   a. charge **b.** mass **c.** wavelength
10. Describe how the following properties of a photon could be measured. Explain in each case what is to be done.
   a. energy **b.** momentum **c.** wavelength

Applying Concepts

11. What is the change in the intensity of red light given off by an incandescent body if the temperature increases from 4000 K to 8000 K?
12. Two iron rods are held in a fire. One glows dark red while the other glows bright orange.
   a. Which rod is hotter?
   b. Which rod is radiating more energy?
13. 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?
14. Potassium in a photocell emits photoelectrons when struck by blue light. Tungsten emits them only when ultraviolet light is used.
   a. Which metal has a higher threshold frequency?
   b. Which metal has a larger work function?
15. Compare the de Broglie wavelength of a baseball moving 21 m/s with the size of the baseball.

Problems

Section 27.1

16. The stopping potential of a certain metal is 5.0 V. What is the maximum kinetic energy of the photoelectrons in
   a. electron volts? **b.** joules?
17. What potential difference is needed to stop electrons having a maximum kinetic energy of 4.8×10^{-19} J?
18. 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?
19. 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?
20. 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?
21. A photocell is used by a photographer 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 the other colors?
22. The threshold frequency of tin is 1.2×10^{15} Hz.
   a. What is the threshold wavelength?
   b. What is the work function of tin?
   c. Electromagnetic radiation with a wavelength of 167 nm falls on tin. What is the kinetic energy of the ejected electrons in eV?
23. What is the momentum of a photon of yellow light whose wavelength is 600 nm?
24. 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?
25. 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?
26. Suppose a 5.0-g object, such as a nickel, vibrates while connected to a spring. Its maximum velocity is 1.0 cm/s.
   a. Find the maximum kinetic energy of the vibrating object.

b. The object emits energy in the form of light of frequency 5.0×10^{14} Hz and its energy is reduced by one step. Find the energy lost by the object.

c. How many step reductions would this object have to make to lose all its energy?

Section 27.2

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

28. An electron is accelerated across a potential difference of 54 V.

a. Find the maximum velocity of the electron.

b. Calculate the de Broglie wavelength of the electron.

29. 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.

30. The kinetic energy of the hydrogen atom electron is 13.65 eV.

a. Find the velocity of the electron.

b. Calculate its de Broglie wavelength.

c. Compare your answer with the radius of the hydrogen atom, 5.19 nm.

31. 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.

32. An electron microscope is useful because the de Broglie wavelength 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?

33. 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 it experienced if it started from rest?

Extra Practice For more practice solving problems, go to Extra Practice Problems, Appendix B.

Critical Thinking Problems

34. A HeNe laser emits photons with a wavelength of 632.8 nm.

a. Find the energy, in joules, of each photon.

b. A typical small laser has a power of 0.5 mW = 5×10^{-4} J/s. How many photons are emitted each second by the laser?

35. The intensity of a light that is just barely visible is 1.5×10^{-11} W/m^2.

a. If this light shines into your eye, passing through the pupil with a diameter of 7.0 mm, what is the power, in watts, that enters your eye?

b. If the light has a wavelength of 550 nm, how many photons per second enter your eye?

Going Further

Applying Calculators A student completed a photoelectric–effect experiment, recording 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 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 Versus Wavelength

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

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