CHAPTER

14

Key Concepts

In this chapter, you will learn about:

- the idea of the quantum
- the wave–particle duality
- basic concepts of quantum theory

Learning Outcomes

When you have completed this chapter, you will be able to:

Knowledge

- describe light using the photon model
- explain the ways in which light exhibits both wave and particle properties
- state and use Planck's formula
- give evidence for the wave nature of matter
- use de Broglie's relation for matter waves

Science, Technology, and Society

- explain the use of concepts, models, and theories
- explain the link between scientific knowledge and new technologies

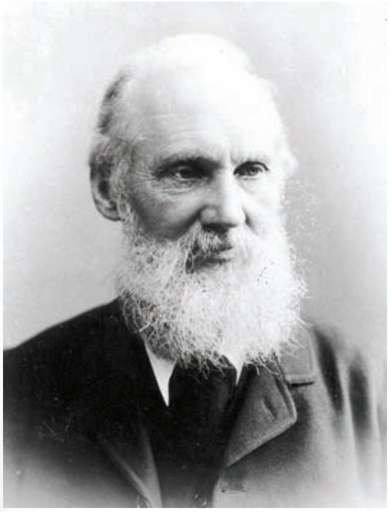
Skills

- observe relationships and plan investigations
- analyze data and apply models
- work as members of a team
- apply the skills and conventions of science

The wave-particle duality reminds us that sometimes truth really *is* stranger than fiction!

Up to this point in the course, you have studied what is known as *classical physics*. Classical physics includes most of the ideas about light, energy, heat, forces, and electricity and magnetism up to about 1900. The golden age of classical physics occurred at the very end of the 19th century. By this time, Newton's ideas of forces and gravitation were over 200 years old, and our knowledge of physics had been added to immensely by the work of James Clerk Maxwell, Michael Faraday, and others. It seemed as though nearly everything in physics had been explained. In the spring of 1900, in a speech to the Royal Institution of Great Britain, the great Irish physicist William Thomson (Figure 14.1) — otherwise known as Lord Kelvin — stated that "… the beauty and clearness of the dynamical theory of light and heat is overshadowed by two clouds…." You could paraphrase Kelvin as saying "the beauty and clearness of *physics* is overshadowed by two clouds." One "cloud" was the problem of how to explain the relationship between the temperature of a material and the colour of light the material gives off. The other "cloud" had to do with an unexpected result in an experiment to measure the effect of Earth's motion on the speed of light.

Kelvin was confident that these two clouds would soon disappear. He was wrong! Before the year was out, the first of these clouds "broke" into a storm the effects of which are still being felt today! In this chapter, you will meet one of the strangest ideas in all of science. In many ways, this chapter represents the end of classical physics. You will learn that light is not only a wave, but also a particle. Stranger still, you will learn that things you thought were particles, such as electrons, sometimes act like waves! Hang on!



◀ **Figure 14.1**

William Thomson (1824–1907) was named Lord Kelvin by Queen Victoria in 1892. He was the first British scientist to be honoured in this way. During his long and illustrious career, Lord Kelvin published over 600 books and papers, and filed more than 70 patents for his inventions. He was one of the driving forces behind the first transatlantic telegraph cable.

info **BIT**

This chapter is about the "cloud" that became quantum theory. In 1905, the other "cloud" became Einstein's theory of special relativity.

14-1 QuickLab

The Relationship Between Temperature and Colour of an Incandescent Object

Problem

What is the relationship between the temperature of a hot, glowing object and the colour of light emitted by the object?

Materials

incandescent (filament-style) light bulb
variable transformer, 0–120 V
transmission-type diffraction grating

Procedure

1. Attach a filament-style light bulb to a variable transformer and slowly increase the voltage.
2. Observe the spectrum produced by the light from the light bulb as it passes through the diffraction grating. For best results, darken the room.

Questions

1. What happens to the temperature of the filament in the light bulb as you increase the voltage output of the transformer?
2. How does the spectrum you observe through the diffraction grating change as you increase the voltage through the filament?
3. As you increase the temperature of the filament, what happens to the colour at which the spectrum appears brightest?
4. You may have noticed that the colour of a flashlight filament becomes reddish as the battery weakens. Suggest why.

Think About It

1. Describe the relationship between the colour of a hot object and its temperature. Note in particular the colour you would first see as the temperature of an object increases, and how the colour changes as the object continues to heat up.
2. What do we mean by the terms “red-hot” and “white-hot”?
3. Which is hotter: “red-hot” or “white-hot”?
4. Is it possible for an object to be “green-hot”? Explain.

Discuss your answers in a small group and record them for later reference. As you complete each section of this chapter, review your answers to these questions. Note any changes in your ideas.

info BIT

Even a great physicist can be wrong! Despite making extremely important contributions to many areas of physics and chemistry, Lord Kelvin has also become famous for less-than-accurate predictions and pronouncements. Here are a few:

- “I can state flatly that heavier-than-air flying machines are impossible.” (1895)
- “There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.” (1900)
- “X rays will prove to be a hoax.” (1899)
- “Radio has no future.” (1897)
- “[The vector] has never been of the slightest use to any creature.”

14.1 The Birth of the Quantum

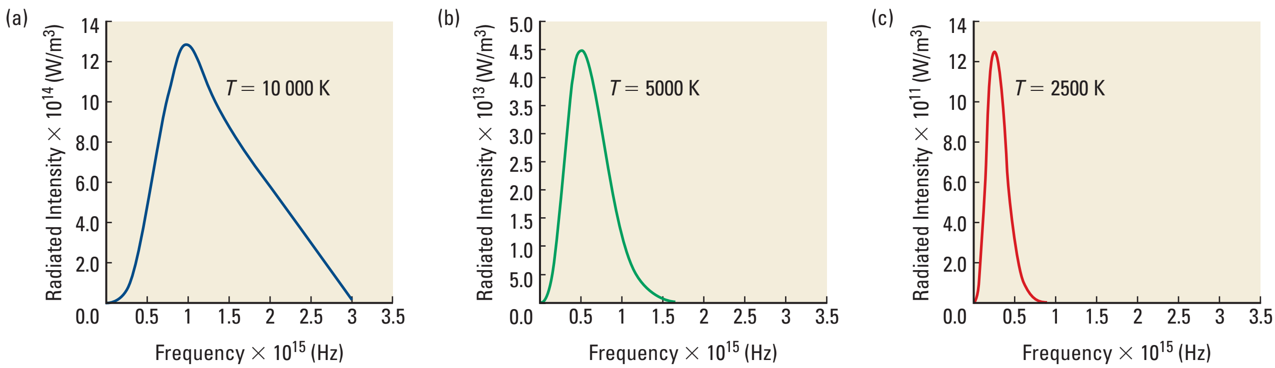
▲ **Figure 14.2** The colour of molten bronze depends on its temperature.

incandescent: glowing with heat

We take for granted the relationship between the colour of a hot, glowing object and its temperature. You know from sitting around a campfire that the end of a metal wiener-roasting stick slowly changes from a dull red to a bright reddish-yellow as it heats up. For centuries, metalworkers have used the colour of molten metal to determine when the temperature is just right for pouring metal into molds in the metal-casting process (Figure 14.2). The association between colour and temperature is so common that you would expect the mathematical relationship between colour and temperature to be simple. That is certainly what classical physicists expected. Despite their best efforts, however, classical physicists were never able to correctly predict the colour produced by an **incandescent** object. What is the connection between temperature and a glowing object's colour?

Figure 14.3 shows three graphs that relate the colours produced by hot objects to their temperatures. The relationship between colour and temperature may be summarized as follows:

1. Hot, glowing objects emit a continuous range of wavelengths and hence a continuous spectrum of colours.
2. For a given temperature, the light emitted by the object has a range of characteristic wavelengths, which determine the object's colour when it glows (Figure 14.2).
3. The hotter an object is, the bluer the light it emits. The cooler an object is, the redder its light is.



▲ **Figure 14.3** Blackbody curves for three different temperatures (Kelvin): 10 000 K, 5000 K, and 2500 K. Frequency is along the horizontal axis, and energy intensity emitted is along the vertical axis. Note that these graphs do not have the same vertical scale. If they did, graph (a) would be 256 times taller than graph (c)!

Concept Check

Next time you are under a dark, clear sky, look carefully at the stars. Some will appear distinctly bluish-white, while others will be reddish or orange in appearance. What do differences in colour tell you about the stars?

Physicists call the graphs in Figure 14.3 **blackbody radiation curves**. The term "**blackbody**," introduced by the German physicist Gustav Kirchhoff in 1862, refers to an object that completely absorbs any light energy that falls on it, from all parts of the electromagnetic spectrum. When this perfect absorber heats up, it becomes a perfect radiator. The energy it reradiates can be depicted as a blackbody curve, which depends on temperature only (Figure 14.3). Hot objects, such as the filament in an incandescent light bulb used in 14-1 QuickLab, or a glowing wiener-roast stick, are good approximations to a blackbody.

Not only did classical physics fail to explain the relationship between temperature and the blackbody radiation curve, it also made a completely absurd prediction: A hot object would emit its energy most effectively at short wavelengths, and that the shorter the wavelength, the more energy that would be emitted. This prediction leads to a rather disturbing conclusion: If you strike a match, it will emit a little bit of light energy at long wavelengths (e.g., infrared), a bit more energy in the red part of the spectrum, more yet in the blue, even more in the ultraviolet, a lot more in the X-ray region, and so on. In short, striking a match would incinerate the entire universe! This prediction was called the *ultraviolet catastrophe*. Fortunately for us, classical physics was incorrect. Figure 14.4 shows a comparison between the prediction made by classical physics and the blackbody radiation curve produced by a hot object.

Quantization and Planck's Hypothesis

In December 1900, Max Planck (Figure 14.5) came up with an explanation of why hot objects produce the blackbody radiation curves shown in Figures 14.3 and 14.4. Planck suggested that the problem with the classical model prediction had to do with how matter could absorb light energy. He discovered that, by limiting the *minimum* amount of energy that any given wavelength of light can exchange with its surroundings, he could reproduce the blackbody radiation curve exactly. The name **quantum** was given to the smallest amount of energy of a particular wavelength or frequency of light that could be absorbed by a body. Planck's hypothesis can be expressed in the following formula, known as **Planck's formula**:

$$E = nhf$$

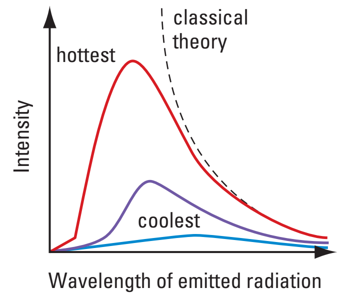
where E is the energy of the quantum, in joules, $n = 1, 2, 3 \ldots$ refers to the *number* of quanta of a given energy, h is a constant of proportionality, called *Planck's constant*, which has the value 6.63×10^{-34} J•s, and f is the frequency of the light.

If energy is transferred in quanta, then the amount of energy transferred must be **quantized**, or limited to whole-number multiples of a smallest unit of energy, the quantum.

Even though Planck's hypothesis could reproduce the correct shape of the blackbody curve, there was no explanation in classical physics for his idea. The concept of the quantum marks the end of classical physics and the birth of quantum physics.

blackbody radiation curve: a graph of the intensity of light emitted versus wavelength for an object of a given temperature

blackbody: an object that completely absorbs any light energy that falls on it



▲ **Figure 14.4** According to classical theory, as an object becomes hotter, the intensity of light it emits should increase and its wavelength should decrease. The graph shows a comparison of the classical prediction (dashed line) and what is actually observed for three objects at different temperatures.

▲ **Figure 14.5** Max Planck (1858–1947) is one of the founders of quantum physics.

quantum: the smallest amount or "bundle" of energy that a wavelength of light can possess (pl. quanta)

Planck's formula: light comes in quanta of energy that can be calculated using the equation $E = nhf$

quantized: limited to whole multiples of a basic amount (quantum)

PHYSICS INSIGHT

Planck's constant can be expressed using two different units:
$h = 6.63 \times 10^{-34}\ \text{J}\cdot\text{s}$ or
$h = 4.14 \times 10^{-15}\ \text{eV}\cdot\text{s}$
Recall that
$1\ \text{eV} = 1.60 \times 10^{-19}\ \text{J}$
or $1\ \text{J} = 6.25 \times 10^{18}\ \text{eV}$.

Concept Check

Show that Planck's formula for one photon can be written as $E = \dfrac{hc}{\lambda}$.

Einstein, Quanta, and the Photon

photon: a quantum of light

In 1905, a young and not-yet-famous Albert Einstein made a very bold suggestion. Planck had already introduced the idea of quantization of energy and the equation $E = hf$. He thought that quantization applied only to matter and how matter could absorb or emit energy. Einstein suggested that this equation implied that light itself was quantized. In other words, Einstein reintroduced the idea that light could be considered a particle or a quantum of energy! This idea was troubling because, as you saw in Chapter 13, experiments clearly showed that light is a wave. In 1926, the chemist Gilbert Lewis introduced the term **photon** to describe a quantum of light. Planck's formula, $E = nhf$, can therefore be used to calculate the energy of one or more photons.

Examples 14.1 and 14.2 allow you to practise using the idea of the photon and Planck's formula.

Example 14.1

How much energy is carried by a photon of red light of wavelength 600 nm?

Given

$n = 1$

$\lambda = 600\ \cancel{\text{nm}} \times \dfrac{1 \times 10^{-9}\ \text{m}}{1\ \cancel{\text{nm}}} = 6.00 \times 10^{-7}\ \text{m}$

Required

photon energy (E)

Analysis and Solution

Since wavelength is given, first find the frequency using the equation $c = f\lambda$, where c is the speed of light, f is frequency, and λ is the wavelength.

$$\begin{aligned} f &= \frac{c}{\lambda} \\ &= \frac{3.00 \times 10^{8}\ \frac{\cancel{\text{m}}}{\text{s}}}{6.00 \times 10^{-7}\ \cancel{\text{m}}} \\ &= 5.00 \times 10^{14}\ \text{Hz} \end{aligned}$$

Then substitute into Planck's formula:

$$\begin{aligned} E &= nhf \\ &= (1)(6.63 \times 10^{-34}\ \text{J}\cdot\cancel{\text{s}})(5.00 \times 10^{14}\ \cancel{\text{s}^{-1}}) \\ &= 3.32 \times 10^{-19}\ \text{J} \end{aligned}$$

Practice Problems

1. What is the energy of a photon of light of frequency 4.00×10^{14} Hz?
2. What is the energy of a green photon of light of wavelength 555 nm?
3. What is 15.0 eV expressed in units of joules?

Answers

1. 2.65×10^{-19} J
2. 3.58×10^{-19} J
3. 2.40×10^{-18} J

It is often more convenient to express the energies of photons in units of electron volts. Since 1 eV = 1.60×10^{-19} J, the energy of the red photon is

$$3.32 \times 10^{-19}\ \cancel{\text{J}} \times \frac{1\ \text{eV}}{1.60 \times 10^{-19}\ \cancel{\text{J}}} = 2.07\ \text{eV}$$

Paraphrase

A red photon of light carries 3.32×10^{-19} J of energy, or about 2.07 eV.

Example 14.2

Your eye can detect as few as 500 photons of light. The eye is most sensitive to light having a wavelength of 510 nm. What is the minimum amount of light energy that your eye can detect?

Given

$\lambda = 510\ \text{nm} = 5.10 \times 10^{-7}\ \text{m}$

$n = 500$ photons

Required

minimum light energy (E)

Analysis and Solution

Since only wavelength is given, determine frequency using the equation $c = f\lambda$:

$$\begin{aligned} f &= \frac{c}{\lambda} \\ &= \frac{3.00 \times 10^{8}\ \frac{\cancel{\text{m}}}{\text{s}}}{5.10 \times 10^{-7}\ \cancel{\text{m}}} \\ &= 5.88 \times 10^{14}\ \text{Hz} \end{aligned}$$

Then apply Planck's formula:

$$\begin{aligned} E &= nhf \\ &= (500)(6.63 \times 10^{-34}\ \text{J}\cdot\cancel{\text{s}})(5.88 \times 10^{14}\ \cancel{\text{s}^{-1}}) \\ &= 1.95 \times 10^{-16}\ \text{J} \end{aligned}$$

Paraphrase

Your eye is capable of responding to as little as 1.95×10^{-16} J of energy.

Practice Problems

1. What is the frequency of a 10-nm photon?
2. What is the energy of a 10-nm photon?
3. How many photons of green light ($\lambda = 550$ nm) are required to deliver 10 J of energy?

Answers

1. 3.0×10^{16} Hz
2. 2.0×10^{-17} J
3. 2.8×10^{19} photons

MINDS ON What's Wrong with This Analogy?

Sometimes the idea of the quantum is compared to the units we use for money. A dollar can be divided into smaller units, where the cent is the smallest possible unit. In what way is this analogy for the quantum accurate and in what way is it inaccurate? Look very carefully at Planck's formula to find the error in the analogy. Try to come up with a better analogy for explaining quantization.

The next example involves rearranging Planck's formula and applying it to find the relationship between the power of a laser pointer and the number of photons it emits.

Example 14.3

How many photons are emitted each second by a laser pointer that has a power output of 0.400 mW if the average wavelength produced by the pointer is 600 nm?

Given

$\lambda = 600 \text{ nm} = 6.00 \times 10^{-7} \text{ m}$
$P = 0.400 \text{ mW} = 4.00 \times 10^{-4} \text{ W}$

Required

number of photons (n)

Analysis and Solution

Since 1 W = 1 J/s, the laser pointer is emitting 4.00×10^{-4} J/s. Therefore, in 1 s the laser pointer emits 4.00×10^{-4} J of energy. By equating this amount of energy to the energy carried by the 600-nm photons, you can determine how many photons are emitted each second using the equation $E = nhf$.

First use the equation $c = f\lambda$ to determine the frequency of a 600-nm photon:

$$f = \frac{c}{\lambda}$$

Substitute this equation into Planck's formula.

$$\begin{aligned} E &= nhf \\ &= nh\left(\frac{c}{\lambda}\right) \\ n &= \frac{E\lambda}{hc} \\ &= \frac{(4.00 \times 10^{-4} \cancel{\text{J}})(6.00 \times 10^{-7} \cancel{\text{m}})}{(6.63 \times 10^{-34} \cancel{\text{J}\cdot\text{s}})\left(3.00 \times 10^{8} \frac{\cancel{\text{m}}}{\cancel{\text{s}}}\right)} \\ &= 1.21 \times 10^{15} \end{aligned}$$

Paraphrase

A laser that emits 1.21×10^{15} photons each second has a power output of 0.400 mW.

Practice Problems

1. How much energy is delivered by a beam of 1000 blue-light photons ($\lambda = 400$ nm)?
2. How many 400-nm blue-light photons per second are required to deliver 10 W of power?

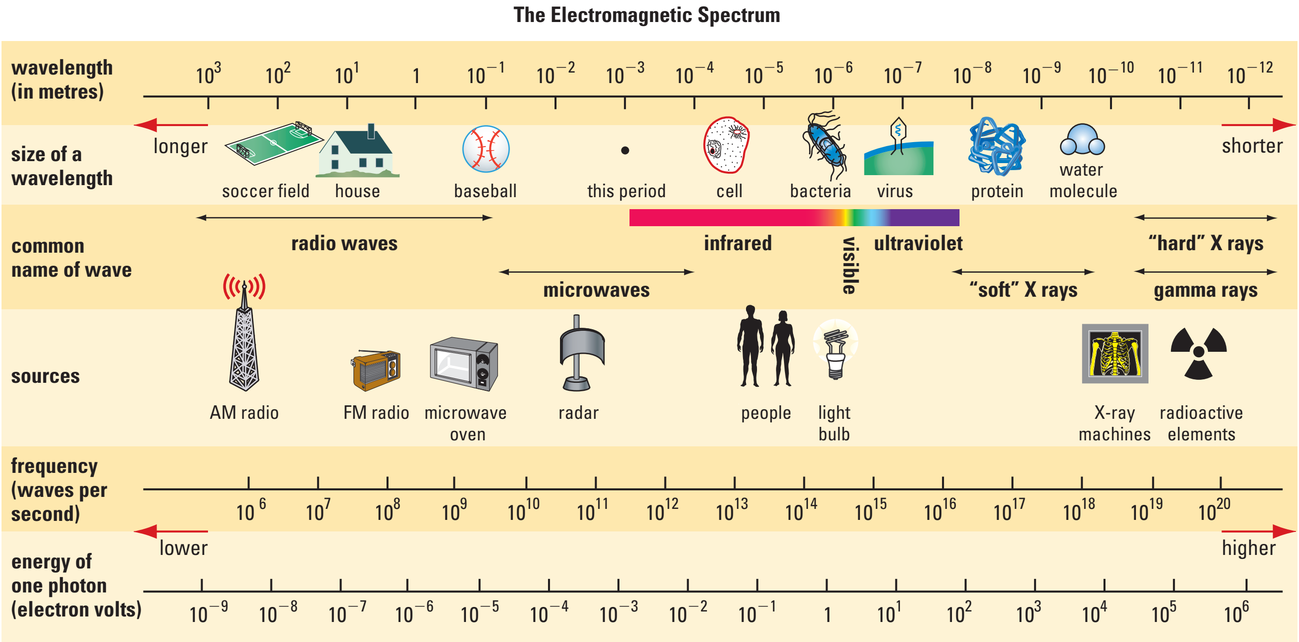
Answers

1. 4.97×10^{-16} J
2. 2.0×10^{19} photons/s

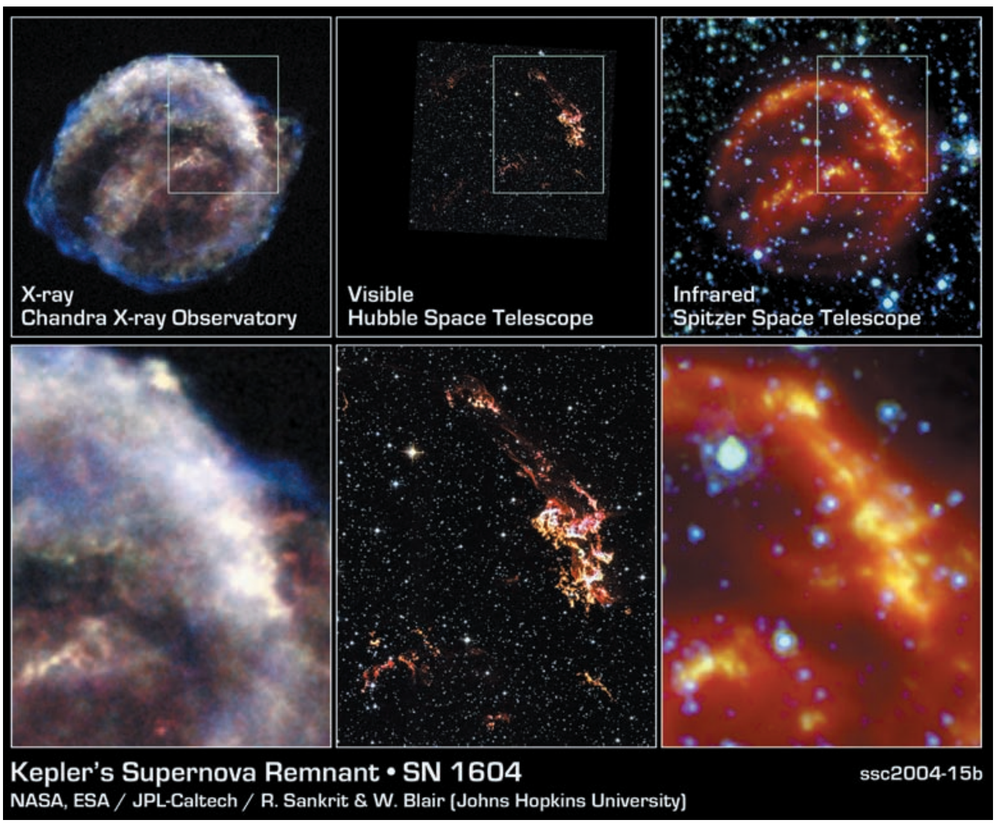
Photons and the Electromagnetic Spectrum

Planck's formula provides a very useful way of relating the energy of a photon to its wavelength or frequency. It shows that a photon's energy depends on its frequency. An X-ray photon is more energetic than a microwave photon, just as X rays have higher frequencies than microwaves. Consequently, it takes a much more energetic process to create a gamma ray or X ray than it does to create a radio wave. Figure 14.6 gives the various photon energies along the electromagnetic spectrum.

X rays, for example, can only be emitted by a very hot gas or by a very-high-energy interaction between particles. Figure 14.7 shows images of the remnants of an exploded star, taken in different parts of the electromagnetic spectrum. Each image shows photons emitted by gases at different temperatures and locations in the remnant.



▲ **Figure 14.6** The energies of photons (in electron volts) along the electromagnetic spectrum



◀ **Figure 14.7** These images of a supernova remnant were taken by the Chandra X-ray space telescope, the Hubble space telescope (visible part of the spectrum), and the Spitzer space telescope (infrared). Each image is produced by gases at different temperatures. X rays are produced by very-high-temperature gases (millions of degrees), whereas infrared light is usually emitted by low-temperature gases (hundreds of degrees).

14.1 Check and Reflect

Knowledge

1. What is the energy of a photon with wavelength 450 nm?

2. What is the wavelength of a photon of energy 15.0 eV?

3. Compare the energy of a photon of wavelength 300 nm to the energy of a 600-nm photon. Which photon is more energetic, and by what factor?

4. (a) What is the frequency of a photon that has an energy of 100 keV?

(b) From what part of the electromagnetic spectrum is this photon?

Applications

5. How many photons of light are emitted by a 100-W light bulb in 10.0 s if the average wavelength emitted is 550 nm? Assume that 100% of the power is emitted as visible light.

6. The Sun provides approximately 1400 W of solar power per square metre. If the average wavelength (visible and infrared) is 700 nm, how many photons are received each second per square metre?

Extensions

7. Suppose that your eye is receiving 10 000 photons per second from a distant star. If an identical star was 10 times farther away, how many photons per second would you receive from that star in one second?

8. Estimate the distance from which you could see a 100-W light bulb. In your estimate, consider each of the following:

- Decide on a representative wavelength for light coming from the light bulb.
- Estimate the surface area of a typical light bulb and use this figure to determine the number of photons per square metre being emitted at the surface of the light bulb.
- Estimate the diameter of your pupil and hence the collecting area of your eye.
- Use the information in Example 14.2 to set a minimum detection limit for light from the light bulb.

Remember that your answer is an estimate. It will likely differ from other students' estimates based on the assumptions you made.

(Hint: The surface area of a sphere is $4\pi r^2$.)

e TEST

To check your understanding of Planck's formula, follow the eTest links at www.pearsoned.ca/school/physicssource.

14.2 The Photoelectric Effect

The secret agent cautiously inches forward and carefully steps over and around the thin, spidery outlines of laser beams focussed on light sensors scattered around Dr. Evil's secret lair.

Is this scenario only the stuff of spy movies? Perhaps, but every time you walk into a shopping mall or have your groceries scanned at the supermarket, you, like the secret agent, are seeing an application of the way in which photons and metals interact. This interaction is called the *photoelectric effect*.

14-2 QuickLab

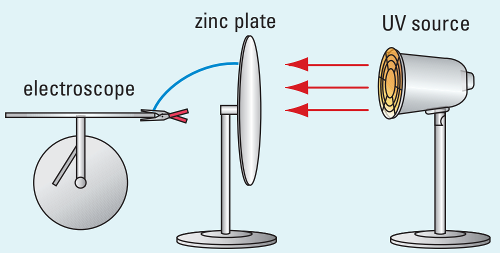
Discharging a Zinc Plate Using UV Light

Problem

Does ultraviolet light cause the emission of electrons from a zinc metal plate?

Materials

electroscope
UV light source
zinc plate
glass plate



▲ **Figure 14.8**

Procedure

1. Attach the zinc plate so that it is in contact with the electroscope.
2. Apply a negative charge to the zinc plate and electroscope. What happens to the vanes of the electroscope? (If you are uncertain how to apply a negative charge, consult your teacher for assistance.)
3. Turn on the UV light source and shine it directly on the zinc plate (see Figure 14.8).
4. Place the glass plate between the UV light source and the zinc plate. Note any change in the behaviour of the vanes of the electroscope. Remove the plate and once again note any change in the response of the vanes.

Questions

1. Why did the vanes of the electroscope deflect when a negative charge was applied?
2. Explain what happened when UV light shone on the zinc plate. Why does this effect suggest that electrons are leaving the zinc plate?
3. Glass is a known absorber of UV light. What happened when the glass plate was placed between the UV source and the electroscope?
4. From your observations, what caused the emission of electrons from the zinc surface? Give reasons for your answer.

CAUTION: UV light is harmful to your eyes. Do not look directly into the UV light source.

In 1887, German physicist Heinrich Hertz conducted a series of experiments designed to test Maxwell's theory of electromagnetic waves. In one of the experiments, a spark jumping between the two metal electrodes of a spark gap was used to create radio waves that could be detected in a similar spark-gap receiver located several metres away. Hertz noticed that his spark-gap receiver worked much better if the small metal electrodes were highly polished. Eventually, it was recognized that it was not the polishing but the ultraviolet light being produced by the main spark in his transmitter that greatly enhanced the ability of sparks to jump in his receiver's spark-gap. Hertz had discovered that some metals emit electrons when illuminated by sufficiently short (high-energy) wavelengths of light. This process is called *photoemission of electrons*, or the **photoelectric effect**. Electrons emitted by this process are sometimes called **photoelectrons**.

photoelectric effect: the emission of electrons when a metal is illuminated by short wavelengths of light

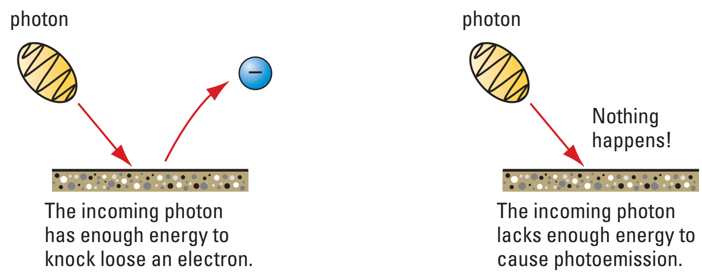
photoelectron: an electron emitted from a metal because of the photoelectric effect

threshold frequency: the minimum frequency that a photon can have to cause photoemission from a metal

How could light waves cause a metal to emit electrons? Experiments showed that the electrons required energies of a few electron volts in order to be emitted by the metal. Perhaps the atoms on the surface of the metal absorbed the energy of the light waves. The atoms would begin to vibrate and eventually absorb enough energy to eject an electron. There is a problem with this theory. According to classical physics, it should take minutes to hours for a metal to emit electrons. Experiments showed, however, that electron emission was essentially instantaneous: There was no measurable delay between the arrival of light on the metal surface and the emission of electrons. To further add to the puzzle, there was a minimum or **threshold frequency, f_0**, of incident light below which no photoemission would occur. If the light shining on the metal is of a frequency lower than this threshold frequency, no electrons are emitted, regardless of the brightness of the light shining on the metal (Figure 14.9).

▼ **Table 14.1** Work Functions of Some Common Metals

Element	Work Function (eV)
Aluminium	4.08
Beryllium	5.00
Cadmium	4.07
Calcium	2.90
Carbon	4.81
Cesium	2.10
Copper	4.70
Magnesium	3.68
Mercury	4.50
Potassium	2.30
Selenium	5.11
Sodium	2.28
Zinc	4.33



▲ **Figure 14.9** If an incident photon has a high enough frequency, an electron will be emitted by the metal surface. If the incoming photon frequency is not high enough, an electron will not be emitted.

Another puzzle was the lack of clear connection between the energy of the electrons emitted and the brightness of the light shining on the metal surface. For a given frequency of light, provided it was greater than the threshold frequency, the emitted electrons could have a range of possible kinetic energies. Increasing the intensity of the light had no influence on the maximum kinetic energy of the electrons.

Einstein's Contribution

The photoelectric effect remained an interesting but completely unexplained phenomenon until 1905. In 1905, Albert Einstein solved the riddle of the photoelectric effect by applying Planck's quantum hypothesis: Light energy arrives on the metal surface in discrete bundles, which are absorbed by atoms of the metal. This process takes very little time and all the energy needed to expel an electron is provided at once. However, photoemission only occurs if the frequency of the incident photons is greater than or equal to the threshold frequency of the metal. Since the frequency of a photon is directly proportional to its energy, as given by Planck's formula, $E = hf$, the incident photons must have the minimum energy required to eject electrons. This minimum energy is known as the **work function**, ***W***. The work function is specific for every metal. Table 14.1 lists the work functions of some common metals. The work function, W, is related to threshold frequency, f_0, by the equation $W = hf_0$. Photons with a frequency greater than the threshold frequency have energy greater than the work function and electrons will be ejected.

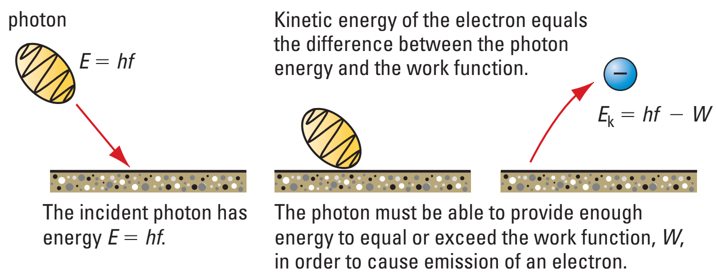
work function: the minimum energy that a photon can have to cause photoemission from a metal; specific for every metal

MINDS ON **Light a Particle? Heresy!**

Suggest reasons why a physicist might argue against Einstein's idea that light is a particle. One such physicist was Robert A. Millikan, whose important experiments on the photoelectric effect were viewed, ironically, as a brilliant confirmation of Einstein's "crazy" idea. How is skepticism both an advantage and a disadvantage to the progress of science?

Millikan's Measurement of Planck's Constant

When photons are absorbed by a metallic surface, either nothing will happen — the photons lack the minimum energy required to cause photoemission — or an electron will be emitted (Figure 14.10).



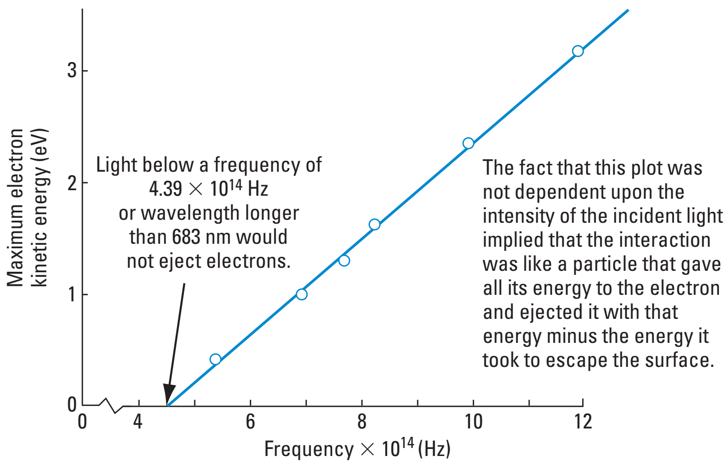
▲ **Figure 14.10** The kinetic energy of an electron emitted during photoemission is equal to the difference between the incident photon's energy and the work needed to overcome the work function for the surface.

▲ **Figure 14.11** Robert Andrews Millikan (1868–1953) was awarded the Nobel Prize in physics in 1923 for his work on determining the charge of an electron, and for his work on the photoelectric effect. Despite his important work on the photoelectric effect, Millikan remained deeply skeptical of Einstein's particle view of light.

One of the most successful experiments to investigate the photoelectric effect was conducted by American physicist Robert Millikan (Figure 14.11) and published in 1916. The main result from Millikan's work is given in Figure 14.12. The graph shows electron kinetic energy as a function of the frequency of the incident light. When the light frequency is *e* **MATH**

Millikan graphed the kinetic energy of the photoelectons as a function of the incident frequency. To explore this relationship closer and to plot a graph like the one shown in Figure 14.12, visit www.pearsoned.com/school/physicssource.

below the threshold frequency, no electrons are ejected. When the light frequency equals the threshold frequency, electrons are ejected but with zero kinetic energy. The threshold frequency is therefore the x-intercept on the graph.



▲ **Figure 14.12** A graph based on the 1916 paper in which Millikan presented the data from his investigation of the photoelectric effect

PHYSICS INSIGHT

$E_k = hf - W$
and
$y = mx + b$
Therefore,
$x_{int} = f_0$
and
$y_{int} = -W$

Once the frequency of the light exceeds the threshold frequency, photoemission begins. As the light frequency increases, the kinetic energy of the electrons increases proportionally. You can express this relationship in a formula by using the law of conservation of energy. The energy of the electron emitted by the surface is equal to the difference between the original energy of the photon, given by $E = hf$, minus the work needed to free the electron from the surface. The equation that expresses this relationship is

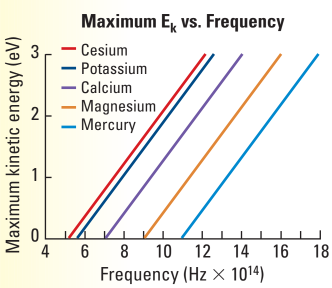
$$E_k = hf - W$$

where E_k is the maximum kinetic energy of the electrons and W is the work function of the metal. You may recall that this equation is an example of the straight-line relationship $y = mx + b$, where m is the slope of the line and b is the y-intercept. The graph in Figure 14.12 shows the linear relationship between the frequency of the incident light falling on a sodium metal surface and the maximum kinetic energy of the electrons emitted by the metal. The slope of this line shows that the energy of the photons is directly proportional to their frequency, and the proportionality constant is none other than Planck's constant. Millikan's photoelectric experiment provides an experimental way to measure Planck's constant. The y-intercept of this graph represents the negative of the work function of the photosensitive surface. The work function can also be determined by measuring the threshold frequency of photons required to produce photoemission of electrons from the metal.

Even though classical physics could not explain the photoelectric effect, this phenomenon still obeys the fundamental principle of conservation of energy, where $E_{Total_{initial}} = E_{Total_{final}}$. The energy of the photon is completely transferred to the electron and can be expressed by the following equation:

$$hf = W + E_k$$

PHYSICS INSIGHT



Different metals have different threshold frequencies, as shown in this graph. Which metal has the highest threshold frequency?

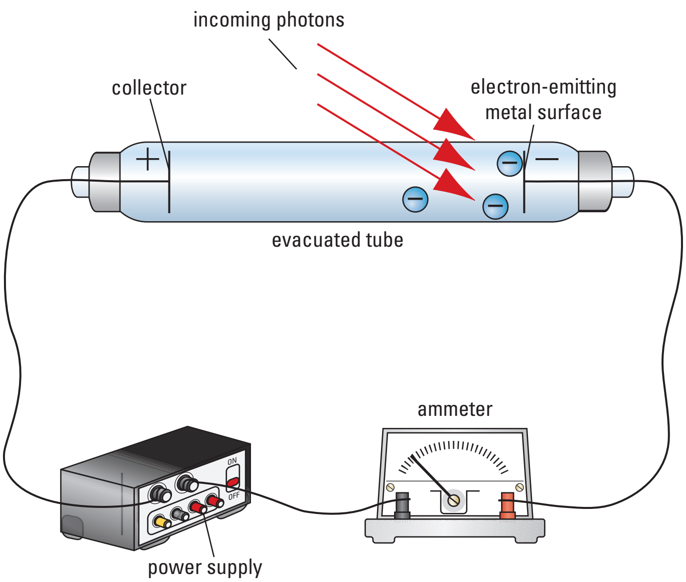
Another way to interpret this equation is that the energy of the photon liberates the electron from the photosensitive surface, and any remaining energy appears as the electron's kinetic energy.

Concept Check

Derive a relationship between energy of a photon (hf) and work function for a metal (W) to determine whether or not photoemission will occur.

Stopping Potentials and Measuring the Kinetic Energy of Photoelectrons

How did Millikan determine the maximum kinetic energy of electrons emitted by a metal surface? Figure 14.13 shows a highly simplified version of his experimental set-up. An evacuated tube contains a photoelectron-emitting metal surface and a metal plate, called the collector. A power supply is connected to the collector and the electron-emitting metal surface. When the power supply gives the collector plate a positive charge, the ammeter registers an electric current as soon as the incoming photons reach the threshold frequency. Any electrons emitted by the metal surface are attracted to the collector and charge begins to move in the apparatus, creating a current.



◀ **Figure 14.13** A simplified diagram depicting an experimental set-up used to investigate the photoelectric effect. When the power supply is connected as shown, the ammeter measures a current whenever the frequency of the incoming light exceeds the threshold frequency for the metal surface.

Concept Check

Explain the role of the collector plate in the photoelectric experiment apparatus in Figure 14.13. If the collector plate is not given a charge, would an electric current still be measured if the incoming photons exceed the threshold frequency?

eSIM

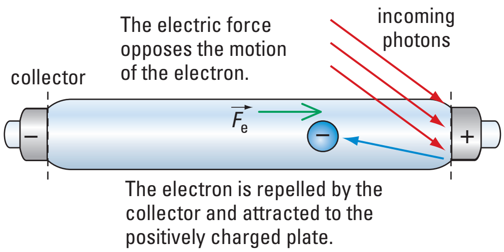
Find out more about the photoelectric effect by doing this simulation. Follow the eSim links at www.pearsoned.ca/school/physicssource.

Now consider what happens if the collector plate is given a negative charge. Instead of being attracted toward the collector, electrons now experience an electric force directed away from the collector. This electric force does work on the photoelectron (Figure 14.14). Photoelectrons will arrive at the collector only if they leave the metal surface with enough kinetic energy to reach the collector.

You can express the final kinetic energy of the electrons in the following way:

$$E_{k_{final}} = E_{k_{initial}} - \Delta E$$

where $E_{k_{final}}$ is the final kinetic energy of the electron, $E_{k_{initial}}$ is its initial kinetic energy, and ΔE is the work done by the electric force.



▲ **Figure 14.14** When the charges on the plates are reversed, the photoelectrons are repelled by the negatively charged collector and pulled back toward the positively charged plate. Only the most energetic electrons will reach the negative plate.

In Chapter 11, you saw that the work done in an electric field of potential V on a charge q is expressed by the equation $\Delta E = qV$. The final kinetic energy of an electron arriving at the collector can now be written as $E_{k_{final}} = E_{k_{initial}} - qV$, where q represents the charge of an electron. If the negative potential on the collector plate is increased, then eventually a point will be reached at which no electrons will be able to reach the collector. At this point, the current in the ammeter drops to zero and the potential difference is now equal to the **stopping potential**. In summary, the current drops to zero when $0 \leq E_{k_{max}} - qV_{stopping}$. The maximum kinetic energy of electrons may now be expressed as

stopping potential: the potential difference for which the kinetic energy of a photoelectron equals the work needed to move through a potential difference, *V*

$$E_{k_{max}} = qV_{stopping}$$

where $V_{stopping}$ is the stopping potential and q is the charge of the electron.

Example 14.4

Blue light shines on the metal surface shown in Figure 14.13 and causes photoemission of electrons. If a stopping potential of 2.6 V is required to completely prevent electrons from reaching the collector, determine the maximum kinetic energy of the electrons. Express your answer in units of joules and electron volts.

Given

$V_{stopping} = 2.6\ \text{V}$

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

Required

maximum kinetic energy of electrons ($E_{k_{max}}$)

Practice Problems

1. What stopping potential will stop electrons of energy 5.3×10^{-19} J?
2. Convert 5.3×10^{-19} J to electron volts.
3. What is the maximum kinetic energy of electrons stopped by a potential of 3.1 V?

Analysis and Solution

Use the equation $E_{k_{max}} = qV_{stopping}$.

$$E_{k_{max}} = (1.60 \times 10^{-19}\ \text{C})(2.6\ \text{V})$$
$$= 4.2 \times 10^{-19}\ \cancel{\text{J}} \times \frac{1\ \text{eV}}{1.60 \times 10^{-19}\ \cancel{\text{J}}}$$
$$= 2.6\ \text{eV}$$

Paraphrase

A stopping potential of 2.6 V will stop electrons of kinetic energy 4.2×10^{-19} J or 2.6 eV.

Answers

1. 3.3 V
2. 3.3 eV
3. 3.1 eV or 5.0×10^{-19} J

Concept Check

Show that the idea of stopping potential can lead directly to the expression $h = \dfrac{qV_{stopping} + W}{f_0}$, where h is Planck's constant, $V_{stopping}$ is the stopping potential, W is the work function, and f_0 is the threshold frequency for emission of electrons from a metal surface.

14-3 Design a Lab

Using the Photoelectric Effect to Measure Planck's Constant

The Question

How can you use the photoelectric effect and the concept of stopping potential to determine Planck's constant?

Design and Conduct Your Investigation

You will need to decide on what equipment to assemble to enable you to relate frequency of incident light to kinetic energy of electrons and stopping potentials. In your design, be sure to address what you will need to measure and what variables will be involved, how to record and analyze your data, and how to use the data collected to answer the question. Prepare a research proposal for your teacher to determine whether your school laboratory has the necessary equipment for this lab, or if alternative approaches may work. Your proposal should include a worked-out sample of how the data you hope to collect will answer the question. Remember to work safely, to clearly identify tasks, and to designate which group members are responsible for each task.

The following example shows how to relate the concepts of threshold frequency and work function.

Example 14.5

Experiments show that the work function for cesium metal is 2.10 eV. Determine the threshold frequency and wavelength for photons capable of producing photoemission from cesium.

Practice Problems

1. Light of wavelength 480 nm is just able to produce photoelectrons when striking a metal surface. What is the work function of the metal?
2. Blue light of wavelength 410 nm strikes a metal surface for which the work function is 2.10 eV. What is the energy of the emitted photoelectron?

Answers

1. 2.59 eV
2. 0.932 eV

Given

$W = 2.10\ \text{eV}$

Required

threshold frequency (f_0)
wavelength (λ)

Analysis and Solution

The work function is the amount of energy needed to just break the photoelectron free from the metal surface, but not give it any additional kinetic energy. Therefore, from $E_k = hf - W$, for threshold frequency, f_0, set $E_k = 0$ J.

First convert the work function to units of joules.

$$\begin{aligned} W &= (2.10\ \cancel{\text{eV}})\left(1.60 \times 10^{-19}\ \frac{\text{J}}{\cancel{\text{eV}}}\right) \\ &= 3.36 \times 10^{-19}\ \text{J} \end{aligned}$$

Now solve for the threshold frequency.

$$\begin{aligned} 0 &= hf_0 - W \\ f_0 &= \frac{W}{h} \\ &= \frac{3.36 \times 10^{-19}\ \cancel{\text{J}}}{6.63 \times 10^{-34}\ \cancel{\text{J}}\cdot\text{s}} \\ &= 5.07 \times 10^{14}\ \text{Hz} \end{aligned}$$

From $c = f\lambda$, the wavelength of this photon is

$$\begin{aligned} \lambda &= \frac{c}{f} \\ &= \frac{3.00 \times 10^{8}\ \frac{\text{m}}{\cancel{\text{s}}}}{5.07 \times 10^{14}\ \cancel{\text{s}^{-1}}} \\ &= 5.91 \times 10^{-7}\ \text{m} \\ &= 591\ \text{nm} \end{aligned}$$

Paraphrase

The threshold frequency for photons able to cause photoemission from cesium metal is 5.07×10^{14} Hz. This frequency corresponds to photons of wavelength 591 nm, which is in the yellow-orange part of the visible spectrum.

You can also use the law of conservation of energy equation for the photoelectric effect to predict the energy and velocity of the electrons released during photoemission.

Example 14.6

Using Table 14.1, determine the maximum speed of electrons emitted from an aluminium surface if the surface is illuminated with 125-nm ultraviolet (UV) light.

Given
$\lambda = 125$ nm
metal = aluminium

Required
maximum speed of electrons (v)

Analysis and Solution
From Table 14.1, the work function for aluminium is 4.08 eV. Convert this value to joules.

$$\begin{aligned} W &= 4.08 \text{ eV} \\ &= (4.08\ \cancel{\text{eV}})\left(1.60 \times 10^{-19}\ \frac{\text{J}}{\cancel{\text{eV}}}\right) \\ &= 6.528 \times 10^{-19} \text{ J} \end{aligned}$$

To determine the energy of the incident photon, use the equation $E = hf = h\left(\frac{c}{\lambda}\right)$.

Incident photon energy is

$$\begin{aligned} E &= h\left(\frac{c}{\lambda}\right) \\ &= (6.63 \times 10^{-34}\ \text{J}\cdot\cancel{\text{s}})\left(\frac{3.00 \times 10^{8}\ \frac{\cancel{\text{m}}}{\cancel{\text{s}}}}{1.25 \times 10^{-7}\ \cancel{\text{m}}}\right) \\ &= 1.591 \times 10^{-18} \text{ J} \end{aligned}$$

To find the kinetic energy of the electrons, use the law of conservation of energy equation for the photoelectric effect, $E_k = hf - W$. Kinetic energy of the electron is

$$\begin{aligned} E_k &= hf - W \\ &= 15.91 \times 10^{-19} \text{ J} - 6.528 \times 10^{-19} \text{ J} \\ &= 9.384 \times 10^{-19} \text{ J} \end{aligned}$$

Finally, use $E_k = \frac{1}{2}mv^2$ to solve for speed. Recall that an electron has a mass of 9.11×10^{-31} kg.

The electron's speed is

$$\begin{aligned} v &= \sqrt{\frac{2E_k}{m}} \\ &= \sqrt{\frac{2(9.384 \times 10^{-19}\text{ J})}{9.11 \times 10^{-31}\text{ kg}}} \\ &= 1.44 \times 10^{6} \text{ m/s} \end{aligned}$$

Paraphrase
The electrons emitted from the aluminium surface will have a maximum speed of 1.44×10^6 m/s.

Practice Problems

1. A photoelectron is emitted with a kinetic energy of 2.1 eV. How fast is the electron moving?
2. What is the kinetic energy of a photoelectron emitted from a cesium surface when the surface is illuminated with 400-nm light?
3. What is the maximum speed of the electron described in question 2?

Answers

1. 8.6×10^5 m/s
2. 1.01 eV
3. 5.95×10^5 m/s

Millikan's work on the photoelectric effect provided critical evidence in eventually demonstrating the particle or quantized nature of light. As you will see in the next chapter, Millikan also performed a key experiment that demonstrated the discrete or "quantized" nature of electrical charge: He showed that the electron is the smallest unit of electrical charge.

14.2 Check and Reflect

Knowledge

1. What is the energy, in eV, of a 400-nm photon?
2. Explain how the concepts of work function and threshold frequency are related.
3. What is the threshold frequency for cadmium? (Consult Table 14.1 on page 712.)
4. Will a 500-nm photon cause the emission of an electron from a cesium metal surface? Explain why or why not.
5. What stopping voltage is needed to stop an electron of kinetic energy 1.25 eV?
6. Explain how stopping potential is related to the maximum kinetic energy of an electron.
7. True or false? The greater the intensity of the light hitting a metal surface, the greater the stopping potential required to stop photoelectrons. Explain your answer.

Applications

The following data are taken from an experiment in which the maximum kinetic energy of photoelectrons is related to the wavelength of the photons hitting a metal surface. Use these data to answer the following questions.

Wavelength (nm)	Kinetic Energy (eV)
500	0.36
490	0.41
440	0.70
390	1.05
340	1.52
290	2.14
240	3.025

8. Convert the wavelengths given in the data table to frequency units and graph them along with the kinetic energy of the photoelectrons. Be sure to plot frequency on the horizontal axis.
9. Give the value of the slope of the graph that you just drew. What is the significance of this value?
10. What metal do you think was used in the previous example? Justify your answer.

Extensions

11. Explain how the photon model of light correctly predicts that the maximum kinetic energy of electrons emitted from a metal surface does not depend on the intensity of light hitting the metal surface.
12. In several paragraphs, identify three common devices that use the photoelectric effect. Be sure to explain in what way these devices use the photoelectric effect.
13. How long would photoemission take from a classical physics point of view? Consider a beam of ultraviolet light with a brightness of 2.0×10^{-6} W and an area of 1.0×10^{-4} m^2 (about the area of your little fingernail) falling on a zinc metal plate. Use 3.5 eV as the energy that must be absorbed before photoemission can occur.
(Hint: Estimate the area of an atom and determine how much of the beam of UV light is being absorbed each second, on average.)

e TEST

To check your understanding of the photoelectric effect, follow the eTest links at www.pearsoned.ca/school/physicssource.

14.3 The Compton Effect

Although Einstein's photon model provided an explanation of the photoelectric effect, many physicists remained skeptical. The wave model of light was so successful at explaining most of the known properties of light, it seemed reasonable to expect that a purely classical explanation of the photoelectric effect would eventually be found. In 1923, however, an experiment by American physicist Arthur Compton (Figure 14.15) provided an even clearer example of the particle nature of light, and finally convinced most physicists that the photon model of light had validity.

Compton studied the way in which electrons scattered X rays in a block of graphite. The X rays were observed to scatter in all directions. This effect was not surprising: Both the wave and particle models of light predicted this outcome. What the wave model could neither predict nor explain, however, was the small change in wavelength that Compton observed in the scattered X ray, and the relationship between the change in wavelength and the angle through which the X ray was scattered. The scattering of an X ray by an electron is now referred to as **Compton scattering**, and the change in wavelength of the scattered X-ray photon is called the **Compton effect** (Figure 14.16).

To understand the Compton effect, you will need to use two of the most central ideas of physics: the law of conservation of momentum and the law of conservation of energy. The interaction between an X-ray photon and an electron must still obey these laws.

By using the particle model of light and Einstein's mass-equivalence equation $E = mc^2$, Compton showed that the momentum of the X ray could be expressed as

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

where p is momentum, h is Planck's constant, and λ is the wavelength of the X ray. Compton was also able to show exactly how the change in wavelength of the scattered X ray is related to the angle through which the X-ray photon is scattered.

Concept Check

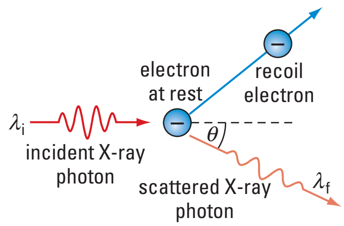
Which of the following photons has the greater momentum: $\lambda_A = 500$ nm or $\lambda_B = 2$ nm? Explain your reasoning.

Compton found that the scattered X ray changed its momentum and energy in a way that was exactly what you would expect if it was a small particle undergoing an elastic collision with an electron. Recall from Chapter 9 that energy and momentum are conserved during an elastic collision.

▲ **Figure 14.15** Arthur Holly Compton (1892–1962) was a pioneer in high-energy physics. He was awarded the Nobel Prize in 1927 for his discovery of the Compton effect, which provided convincing evidence for the photon model of light.

Compton scattering: the scattering of an X ray by an electron

Compton effect: the change in wavelength of the scattered X-ray photon



▲ **Figure 14.16** When an electron scatters an X ray, both momentum and energy are conserved. Compton scattering behaves like an elastic collision between a photon and an electron.

The laws of conservation of energy and of momentum can be applied to the X ray and the electron in the following way:

- The total momentum of the incident X-ray photon must equal the total momentum of the scattered X ray and the scattered electron.
- The total energy of the incident X-ray photon and the electron must equal the total energy of the scattered X ray and the scattered electron.

Concept Check

Study Figure 14.16. Define the direction of the incident X-ray photon as the positive x-direction and the upward direction as the positive y-direction. Suppose the incident X-ray photon has a wavelength of λ_i and the scattered X-ray photon has a wavelength λ_f.

1. Derive an expression for the x and y components of the momentum of the scattered photon.
2. Explain how your answer to question 1 gives you the x and y components of the electron's momentum.
3. How much energy was transferred to the electron in this interaction? Derive a simple expression for the electron's final energy.

Compton derived the following relationship between the change in the wavelength of the scattered photon and the direction in which the scattered photon travels:

$$\begin{aligned}\Delta\lambda &= \lambda_f - \lambda_i \\ &= \frac{h}{mc}(1 - \cos\theta)\end{aligned}$$

where m is the mass of the scattering electron and θ is the angle through which the X ray scatters. The full derivation of this equation requires applying Einstein's theory of relativity and a lot of algebra! The central concepts behind this equation, however, are simply the laws of conservation of energy and of momentum. As well, this equation is exactly consistent with Einstein's idea that the X-ray photon collides with the electron as if it were a particle.

MINDS ON Heisenberg's Microscope Problem

Suggest how Compton scattering shows that it is impossible to "see" an electron. In particular, why is it that we can only see where an electron was and not where it is? (Hint: Think about what photons are doing when you look at something.) This question is sometimes referred to as Heisenberg's microscope problem.

Example 14.7

What is the maximum change in wavelength that a 0.010-nm X-ray photon can undergo by Compton scattering with an electron? Does initial wavelength (0.010 nm) matter in this example?

Given

$\lambda_i = 0.010$ nm

Required

change in wavelength ($\Delta\lambda$)

Analysis and Solution

Maximum change will occur when the X ray is scattered by the greatest possible amount, that is, when the X ray is *back-scattered*. From the Compton effect equation,

$\Delta\lambda = \lambda_f - \lambda_i = \frac{h}{mc}(1 - \cos\theta)$, the maximum value for $\Delta\lambda$ occurs when the term $(1 - \cos\theta)$ is a maximum. This occurs when $\theta = 180°$ and $\cos\theta = -1$, so $(1 - \cos\theta)$ becomes $(1 - (-1)) = 2$. Use this relation to determine the largest possible change in wavelength of the scattered X-ray photon.

$$\begin{aligned}\Delta\lambda &= \frac{h}{mc}(1 - \cos\theta)\\ &= \frac{2h}{mc}\\ &= \frac{2(6.63 \times 10^{-34}\ \text{J}\cdot\text{s})}{(9.11 \times 10^{-31}\ \text{kg})(3.00 \times 10^{8}\ \text{m/s})}\\ &= 4.85 \times 10^{-12}\ \text{m}\end{aligned}$$

Paraphrase

The maximum change in wavelength of a photon during Compton scattering is only 4.85×10^{-12} m. This change is independent of the initial wavelength of the photon.

Practice Problems

1. What is the energy of an X ray of wavelength 10 nm?
2. What is the momentum of an X ray of wavelength 10 nm?
3. If a 10-nm X ray scattered by an electron becomes an 11-nm X ray, how much energy does the electron gain?

Answers

1. 2.0×10^{-17} J
2. 6.6×10^{-26} N•s
3. 1.8×10^{-18} J

You can also use the Compton equation to determine the final wavelength of a photon after scattering, as you will see in the next example.

Example 14.8

An X-ray photon of wavelength 0.0500 nm scatters at an angle of 30°. Calculate the wavelength of the scattered photon.

Given

$\lambda_i = 0.0500$ nm

$\theta = 30°$

Required

final wavelength (λ_f)

Analysis and Solution

Rearrange the Compton equation to solve for final wavelength. Recall that the mass of an electron is 9.11×10^{-31} kg.

$$\begin{aligned}\Delta\lambda &= \lambda_f - \lambda_i \\ &= \frac{h}{mc}(1 - \cos\theta) \\ \lambda_f &= \lambda_i + \Delta\lambda \\ &= \lambda_i + \frac{h}{mc}(1 - \cos\theta) \\ &= 0.0500 \text{ nm} + \frac{6.63 \times 10^{-34}\ \text{J}\cdot\text{s}}{(9.11 \times 10^{-31}\ \text{kg})(3.00 \times 10^{8}\ \text{m/s})}(1 - \cos 30°) \\ &= 0.0500 \text{ nm} + 0.000\,325 \text{ nm} \\ &= 0.0503 \text{ nm}\end{aligned}$$

Paraphrase

The X-ray photon changes wavelength by 0.0003 nm to become a photon of wavelength 0.0503 nm.

Practice Problem

1. An X ray of wavelength 0.010 nm scatters at 90° from an electron. What is the wavelength of the scattered photon?

Answer

1. 0.012 nm

For many physicists, the Compton effect provided the final piece of evidence they needed to finally accept Einstein's idea of the particle nature of light. The Compton effect also describes one of the most fundamental phenomena — the interaction of light with matter.

14.3 Check and Reflect

Knowledge

1. What is the momentum of a 500-nm photon?
2. Photon A has a wavelength three times longer than photon B. Which photon has the greatest momentum and by what factor?
3. A photon has a momentum of 6.00×10^{-21} kg·m/s. What is the wavelength and energy of this photon?
4. Identify the part of the electromagnetic spectrum of the photon in question 3.
5. True or false? One of the major differences between classical physics and quantum physics is that the laws of conservation of energy and momentum do not always work for quantum physics. Explain your answer.

Applications

6. What is the wavelength of a 100-keV X-ray photon?
7. An X-ray photon of wavelength 0.010 nm strikes a helium nucleus and bounces straight back. If the helium nucleus was originally at rest, calculate its velocity after interacting with the X ray.

Extension

8. In order to see an object, it is necessary to illuminate it with light whose wavelength is smaller than the object itself. According to the Compton effect, why is illumination a problem if you wish to see a small particle, such as a proton or an electron?

e TEST

To check your understanding of the Compton effect, follow the eTest links at www.pearsoned.ca/school/physicssource.

14.4 Matter Waves and the Power of Symmetric Thinking

▲ **Figure 14.17** Louis de Broglie (1892–1987) was the first physicist to predict the existence of matter waves.

wave-particle duality: light has both wave-like and particle-like properties

If waves (light) can sometimes act like particles (photons), then why couldn't particles, such as electrons, sometimes act like waves? Louis de Broglie (pronounced "de Broy") (Figure 14.17), a young French Ph.D. student, explored this question in 1924 in a highly imaginative and perplexing thesis. The idea seemed so strange that despite no obvious errors in his argument, the examining committee was reluctant to pass de Broglie. Fortunately, a copy of his thesis was sent to Albert Einstein, who recognized at once the merit in de Broglie's hypothesis. Not only was de Broglie awarded his Ph.D., but his hypothesis turned out to be correct!

De Broglie's argument is essentially one of symmetry. As both the photoelectric effect and the Compton effect show, light has undeniable particle-like, as well as wave-like, properties. This dichotomy is called the **wave-particle duality**. In reality, light is neither a wave nor a particle. These ideas are classical physics ideas, but experiments were revealing subtle and strange results. What light is depends on how we interact with it. De Broglie's hypothesis completes the symmetry by stating that what we naturally assume to be particles (electrons, for example) can have wave-like properties as well. At the atomic level, an electron is neither a wave nor a particle. What an electron is depends on how we interact with it.

De Broglie arrived at his idea by tying together the concepts of momentum and wavelength. Using Compton's discovery relating momentum and wavelength for X-ray photons, de Broglie argued that anything that possessed momentum also had a wavelength. His idea can be expressed in a very simple form:

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

where h is Planck's constant, p is momentum, and λ is de Broglie's wavelength.

De Broglie's Wave Equation Works for Both Light and Electrons

Project **LINK**

How important is de Broglie's hypothesis to our current understanding of the nature of light and matter?

De Broglie's hypothesis states that anything that has momentum must obey the following wavelength-momentum equations:

For light: Maxwell's law of electromagnetism shows that the momentum of a light wave can be written as $p = \frac{E}{c}$, where E is the energy of the light and c is the speed of light. But Planck's formula states that $E = hf$. Therefore, $p = \frac{hf}{c}$. Substituting this equation into de Broglie's wave equation, you obtain $\lambda = \frac{h}{\frac{hf}{c}} = \frac{c}{f}$, which is the wavelength-frequency relation. It tells you that a photon of light has a wavelength!

For electrons: If an electron is moving with a velocity, v, that is *much less than the speed of light*, then its momentum is $p = mv$ and de Broglie's relationship is $\lambda = \frac{h}{p} = \frac{h}{mv}$. For electrons (or any other particles) moving at velocities approaching the speed of light, the expression $\lambda = \frac{h}{p}$ is still applicable.

PHYSICS INSIGHT

Einstein showed that, as objects' speeds approach the speed of light, the familiar expression for momentum, $p = mv$, must be replaced by the more complicated equation

$p = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}$, where

c is the speed of light.

THEN, NOW, AND FUTURE The Electron Microscope

The Electron Microscope

The idea of matter waves is not simply abstract physics that has no practical application. The wave nature of electrons has been used to build microscopes capable of amazing magnification.

The reason for their amazing magnification lies in the extremely small wavelengths associated with electrons. The usable magnification of a microscope depends inversely on the wavelength used to form the image. In a transmission electron microscope (TEM, Figure 14.18), a series of magnets (magnetic lenses) focusses a beam of electrons and passes the beam through a thin slice of the specimen being imaged.

▲ **Figure 14.18** A modern transmission electron microscope

Modern TEMs are capable of reaching very high magnification and imaging at the atomic level.

The scanning electron microscope (SEM) is similar to the TEM but differs in one important way: Electrons are reflected off the sample being imaged. SEM images have a remarkable three-dimensional appearance (Figure 14.19).

▲ **Figure 14.19** An SEM view of an ant's head

Questions

1. Find out more about the varieties of electron microscopes in use. Search the Internet, using key words such as electron microscope, TEM, or SEM, to learn about at least three different kinds of electron microscopes. Summarize your findings in the following way:
   - name (type) of microscope
   - how it differs from other electron microscopes in use and operation
   - typical applications and magnifications
2. The magnification of a microscope depends inversely on the wavelength used to image a specimen. The very best quality light microscopes typically have maximum magnifications of 1000 to 4000 times. Modern TEMs use electrons accelerated to energies of over 100 keV to observe specimens. Estimate the possible range of magnifications that can be achieved using a TEM by considering the following:
   - What is a reasonable choice for the wavelength used in a light microscope?
   - What is the wavelength of a 100-keV electron?
   - How do the wavelengths of the light and of the electrons compare?

(Note: Your answer will likely be an overestimate. The actual magnification of electron microscopes is limited by the ability of the magnetic lenses to focus the electron beam. TEMs are capable of achieving magnifications as high as 500 000 times!)

The next two examples apply the de Broglie relationship between momentum and wavelength.

Example 14.9

What is the momentum of a 500-nm photon of green light?

Given

$\lambda = 500 \text{ nm}$

Required

momentum (p)

Analysis and Solution

To find the photon's momentum, apply de Broglie's equation:

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

$$= \frac{6.63 \times 10^{-34} \text{ J}\cdot\text{s}}{500 \times 10^{-9} \text{ m}}$$

$$= 1.33 \times 10^{-27} \text{ N}\cdot\text{s}$$

Paraphrase

The photon has a momentum of 1.33×10^{-27} N•s.

Practice Problem

1. What is the momentum of a 0.010-nm X ray?

Answer

1. 6.6×10^{-23} kg•m/s

e MATH

De Broglie showed how electrons can be thought of as waves and related the speed of an electron to its wavelength. Einstein's work showed that as the speed of the electron became greater than 10% of the speed of light, relativistic effects has to be taken into account (see Physics Insight p. 727) To explore how the wavelength of an electron is a function of its speed, including relativistic effects, visit www.pearsoned.ca/school/physicssource.

The next example shows how to calculate the wavelength of an electron, thus illustrating that particles have a wave nature.

Example 14.10

What is the wavelength of an electron moving at 1.00×10^4 m/s?

Given

$v = 1.00 \times 10^4 \text{ m/s}$

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

Required

wavelength (λ)

Analysis and Solution

To find the electron's wavelength, first find its momentum and then rewrite de Broglie's equation:

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

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

$$= \frac{6.63 \times 10^{-34} \text{ J}\cdot\text{s}}{(9.11 \times 10^{-31} \text{ kg})(1.00 \times 10^4 \text{ m/s})}$$

$$= 7.28 \times 10^{-8} \text{ m} = 72.8 \text{ nm}$$

Paraphrase

The electron has a de Broglie wavelength of 7.28×10^{-8} m or 72.8 nm.

Practice Problems

1. What is the wavelength of a proton moving at 1.0×10^5 m/s?
2. What is the speed of an electron that has a wavelength of 420 nm?

Answers

1. 4.0×10^{-12} m
2. 1.73×10^3 m/s

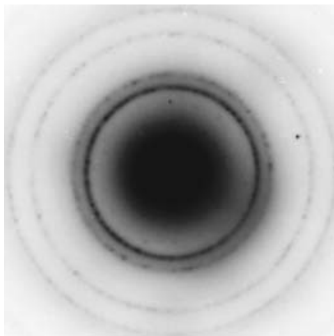
De Broglie's idea completes the concept of the wave-particle duality of light. Wave-particle duality combines two opposing ideas and teaches us that, at the atomic level, it is essential to use both ideas to accurately model the world.

De Broglie's Wave Hypothesis: Strange but True!

Experimental proof of de Broglie's hypothesis came very quickly and by accident. Between 1925 and 1927, American physicists C. J. Davisson and L. H. Germer, and British physicist G. P. Thomson (Figure 14.20, son of J. J. Thomson, discoverer of the electron) independently provided evidence that electrons can act like waves.

The original Davisson and Germer experiment was an investigation of how electrons scattered after hitting different kinds of metallic surfaces. To prevent an oxide layer from contaminating the surfaces, the scattering was done inside a vacuum tube. In one test on a nickel surface, the vacuum tube cracked and the vacuum was lost, unbeknownst to Davisson and Germer. The nickel surface oxidized into a crystalline pattern. What Davisson and Germer observed was a very puzzling pattern: Scattering occurred in some directions and not in others. It was reminiscent of a pattern of nodes and antinodes (Figure 14.21). A simplified version of a typical Davisson–Germer experiment is shown in Figure 14.22(a). The graph in Figure 14.22(b) shows the kind of data that Davisson and Germer found.

▲ **Figure 14.20** George Paget Thomson (1892–1975) was co-discoverer of matter waves with Davisson and Germer. One of the great ironies of physics is that Thomson played an instrumental role in showing that electrons can act like waves. Thirty years earlier, his father had shown that the electron was a particle!

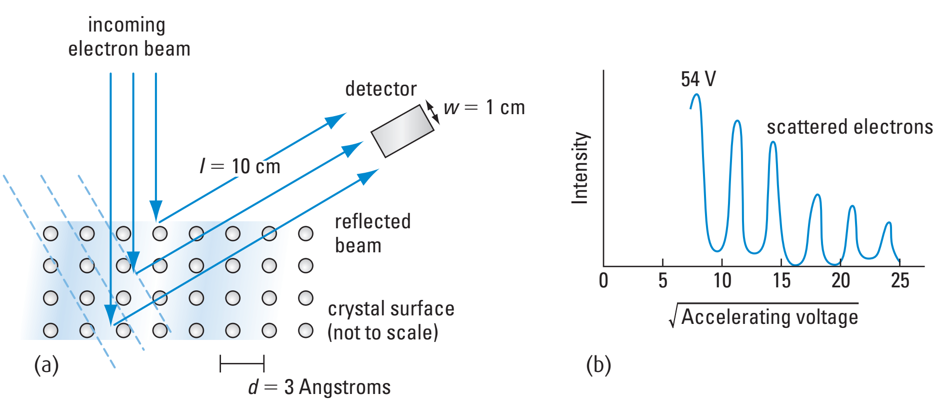


▲ **Figure 14.21** This image was produced by electrons scattered by gold atoms on the surface of a thin gold film. The bright concentric rings are antinodes produced by the constructive interference of electron waves.

MINDS ON Interpret the Graph

(a) Look at the graph in Figure 14.22(b). Explain why it makes sense to interpret the pattern as one of nodes and antinodes. What is happening at each of the nodes?
(b) What would you have to do to change the wavelength of the electrons used in an electron diffraction experiment?

When Davisson and Germer began their experiments, they were unaware of de Broglie's work. As soon as they learned of de Broglie's hypothesis, however, they realized that they had observed electron-wave interference! Over the next two years, they and G. P. Thomson in Scotland refined the study of electron-wave interference and provided beautiful experimental confirmation of de Broglie's hypothesis. In 1937, Davisson and Thomson received a Nobel Prize for the discovery of "matter waves."



◀ **Figure 14.22** (a) A schematic of a typical Davisson–Germer experiment in which atoms on the surface of a metal scatter a beam of electrons. For specific angles, the electrons scatter constructively and the detector records a large number of electrons, shown in the graph in (b). (b) In this graph, a high intensity means that more electrons are scattered in that direction, creating an antinode, or constructive interference. Similarly, a low intensity can be interpreted as a node, or destructive interference.

PHYSICS INSIGHT

Manipulating the accelerating voltage in a Davisson-Germer experiment changes the speed of the incident electrons and, therefore, their wavelength.

Example 14.11

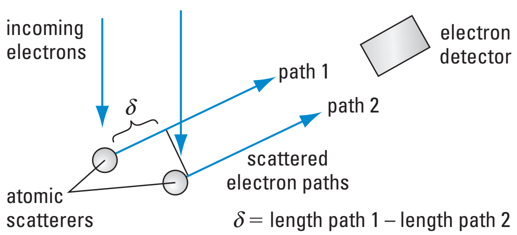
Explain conceptually how the wave properties of electrons could produce the interference pattern shown in Figure 14.21.

Given

You know that electrons have wavelike properties and that electrons are being scattered from atoms that are separated by distances comparable to the size of the electron wavelength.

Analysis

Figure 14.23 shows electron waves leaving from two different atomic scatterers. You can see that path 1 is a little longer than path 2, as denoted by the symbol δ. This difference means that a different number of electron wavelengths can fit along path 1 than along path 2. For example, if the path difference is $\frac{1}{2}\lambda$, $\frac{3}{2}\lambda$, or any odd half-multiple of λ, then, when the electron waves combine at the detector, a complete cancellation of the electron wave occurs, forming a node. On the other hand, if the path difference is a whole-number multiple of λ, then constructive interference occurs, forming an antinode. The Davisson–Germer experiment provided graphic evidence of the correctness of de Broglie's hypothesis.



▲ **Figure 14.23**

De Broglie's Hypothesis — A Key Concept of Quantum Physics

Despite its simplicity, de Broglie's wave hypothesis heralded the true beginning of quantum physics. You will now explore two of the consequences that follow from de Broglie's equation.

De Broglie's Equation "Explains" Quantization of Energy

Imagine that you drop a small bead into a matchbox, close the matchbox, and then gently place the matchbox on a level tabletop. You then ask, "What is the kinetic energy of the bead?" The answer may seem obvious and not very interesting: The energy is 0 J because the bead is not moving. If, however, you could shrink the box down to the size of a molecule and replace the bead with a single electron, the situation becomes very different. You can sometimes model molecules as simple boxes. The particle-in-a-box model shows how the wave nature of electrons (and all other particles) predicts the idea of quantization of energy.

MINDS ON What's Different Now?

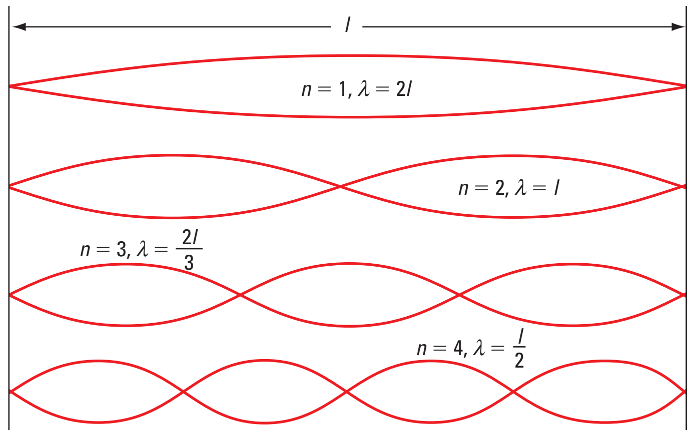
From a quantum point of view, explain why it becomes problematic to put a particle in a box.

In Chapter 8, section 8.3, you learned about standing waves and resonance. These concepts apply to all waves. Because an electron behaves like a wave as well as like a particle, it has a wavelength, so the ideas of resonance and standing waves also apply to the electron.

In order to fit a wave into a box, or finite space, the wave must have a node at each end of the box, and its wavelength must be related to the length of the box in the following way:

$$\lambda_n = \frac{2l}{n}$$

where n is a whole number ($n = 1, 2, 3, \ldots$). Since there is a node at each end of the box, you can think of n as equivalent to the number of half-wavelengths that can fit in the space l, or length of the box (Figure 14.24). The longest possible standing wave that can fit into the box has a wavelength of $\lambda = 2l$, where $n = 1$.



▲ **Figure 14.24** Standing wave patterns for waves trapped inside a box of length l

Because the electron is a standing wave, it cannot be at rest. Consequently, it must have a minimum amount of kinetic energy:

$$\begin{aligned} E_\mathrm{k} &= \frac{1}{2}mv^2 \times \frac{m}{m} \\ &= \frac{m^2v^2}{2m} \\ &= \frac{p^2}{2m} \qquad \text{since } p = mv \end{aligned}$$

where p is the momentum and m is the mass of the electron. Recall that de Broglie's equation shows that the momentum of an electron is inversely related to its wavelength: $\lambda = \dfrac{h}{p}$.

PHYSICS INSIGHT

The particle-in-a-box model is very useful. It can be used to describe such diverse phenomena as small-chain molecules, tiny nano-scale electronics, and the nucleus of an atom. Depending on the situation, the "box" can have one dimension (for a long-chain molecule), two, or three dimensions. Models and modelling form an essential part of the physicist's imaginative "toolbox."

Using de Broglie's equation to relate the momentum of the electron to the length of the box, you can then write:

$$E_k = \frac{p^2}{2m} = \frac{\left(\frac{h}{\lambda}\right)^2}{2m} = \frac{h^2}{2m\lambda^2}$$

From $\lambda_n = \frac{2l}{n}$, when $n = 1$, $\lambda = 2l$. Therefore,

$$E_k = \frac{h^2}{2m(2l)^2} = \frac{h^2}{8ml^2}$$

This equation represents the minimum kinetic energy of an electron.

What if you wanted to give the electron more energy? To have more energy, the electron must have the right momentum-wavelength relation to fit the next standing wave pattern (Figure 14.24). The electron's wavelength is, therefore,

$$\lambda_{n=2} = \frac{2l}{2} = l$$

Substituting into the equation for the kinetic energy of the electron,

$$E_{n=2} = \frac{p^2}{2m} = \frac{h^2}{2m(l)^2} = \frac{h^2}{2ml^2} = 4E_{n=1s}$$

The energy of a particle in a box is given by the general formula

$$E_n = \frac{n^2h^2}{8ml^2},\ n = 1, 2, 3, \ldots$$

These equations demonstrate that energy is quantized for the particle-in-a-box model. As with photons, quantization means that the electron can have only specific amounts or quanta of energy. (Refer to section 14.1.)

Example 14.12

Nanotechnology is one of the hottest areas in physics today. It is now possible to create tiny electric circuits in which electrons behave like particles in a box. Imagine an electron confined to a tiny strip 5.0 nm long. What are three possible energies that the electron could have?

Given

$l = 5.0$ nm

$n = 1, 2, 3$

Required

electron energies (E_1, E_2, E_3)

Practice Problems

1. What is the maximum wavelength for an electron confined to a box of length $l = 1.0$ nm?
2. How much momentum does the electron in question 1 have?

Analysis and Solution

$$E_n = \frac{n^2h^2}{8ml^2},\ n = 1, 2, 3, \ldots$$

Substitute $n = 1$ into the expression for energy:

$$\begin{aligned} E_1 &= \frac{(1^2)h^2}{8ml^2} \\ &= \frac{(1)(6.63 \times 10^{-34}\ \text{J}\cdot\text{s})^2}{8(9.11 \times 10^{-31}\ \text{kg})(5.0 \times 10^{-9}\ \text{m})^2} \\ &= 2.4 \times 10^{-21}\ \text{J} \end{aligned}$$

Calculate any other energy by noting that

$$E_n = n^2\frac{h^2}{8ml^2} = n^2E_1$$

$$E_2 = (2)^2\,E_1 = 4(2.4 \times 10^{-21}\ \text{J}) = 9.7 \times 10^{-21}\ \text{J}$$

$$E_3 = (3)^2\,E_1 = 9(2.4 \times 10^{-21}\ \text{J}) = 2.2 \times 10^{-20}\ \text{J}$$

$$E_n = n^2(2.4 \times 10^{-21}\ \text{J})$$

Paraphrase

An electron confined to a space 5.0 nm long can only have energies that are whole-square multiples of 2.4×10^{-21} J. Three possible energies of the electron are, therefore, 2.4×10^{-21} J, 9.7×10^{-21} J, and 2.2×10^{-20} J.

3. What is the minimum energy that an electron can have when confined to a box of length $l = 1.0$ nm?

Answers

1. 2.0 nm
2. 3.3×10^{-25} kg·m/s
3. 6.0×10^{-20} J

Concept Check

Refer to Figure 14.24. What happens to the minimum possible energy of a particle in a box when you shrink the box? How would the minimum energy of particles in the nucleus of an atom (about 10^{-15} m across) compare to the minimum energy of an electron in the atom itself (about 10^{-10} m across)?

MINDS ON Planck in a Box

Argue that the particle-in-a-box model illustrates Planck's discovery of quantization, and also demonstrates Planck's radiation law.

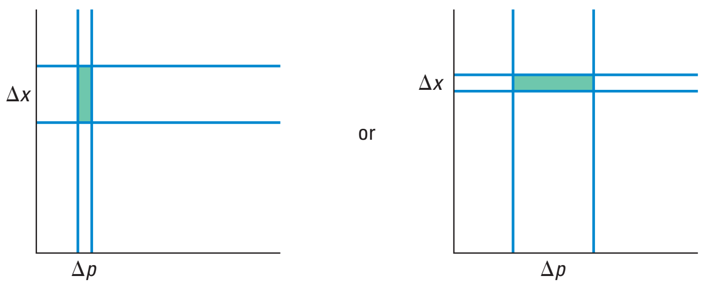
▲ **Figure 14.25** Werner Heisenberg (1901–1976) was one of the most influential physicists of the 20th century and a key developer of modern quantum theory.

Heisenberg's Uncertainty Principle

Consider what you have just learned about the minimum energy of a particle in a box. The smaller you make the box, the shorter is the wavelength of the particle. Furthermore, because wavelength and momentum are inversely related, the shorter the wavelength, the greater is the momentum of the particle. The greater the momentum, the faster, on average, the particle is moving at any instant.

In 1927, the young German physicist Werner Heisenberg (Figure 14.25) realized that the particle-in-a-box model of quantum mechanics has a troubling limitation built into it. Think of the size of the box as indicating the possible uncertainty in the location of the particle. The smaller the box is, the more precisely you know the location of the particle. At the same time, however, the smaller the box is, the greater the momentum and the greater the range of possible momentum values that the particle could have at any instant.

Figure 14.26 illustrates this idea by plotting the uncertainty in position of the particle, Δx (on the vertical axis), and the uncertainty in its momentum, Δp (on the horizontal axis), as strips that intersect. The shaded areas in Figure 14.26 represent the product of uncertainty in position (Δx) and uncertainty in momentum (Δp).



▲ **Figure 14.26** A graphical depiction of the uncertainty in both position and momentum for a particle in a box

PHYSICS INSIGHT

According to the particle-in-a-box model, the smaller the space in which a particle is confined, the greater the kinetic energy, and hence momentum, of that particle. If you think of the length of the box as setting the possible range in location for a particle, then this quantity also tells you how precisely you know the position of the particle. This range is Δx. In the same way, the possible range in momentum is Δp.

Heisenberg's troubling finding was that, due to the wave nature of all particles, it is impossible to know both the position and momentum of a particle with unlimited precision *at the same time*. The more precisely you know one of these values, the less precisely you can know the other value.

To derive the formula for uncertainty in position and momentum of a particle, note that the length of the box is related to the wavelength of the particle:

$$\Delta x \approx \text{length of box} = l$$

$$\lambda = 2l \quad \left(\text{From } \lambda_n = \frac{2l}{n},\ \lambda = 2l \text{ when } n = 1.\right)$$

$$\Delta x \approx \frac{\lambda}{2}$$

Similarly, from de Broglie's equation $\lambda = \frac{h}{p}$, the uncertainty in momentum is

$$\Delta p \approx \text{range in momentum} = \frac{h}{\lambda}$$

The product of uncertainty in position and uncertainty in momentum can be expressed as

$$\Delta x \Delta p \approx \left(\frac{\lambda}{2}\right)\left(\frac{h}{\lambda}\right)$$

$$\Delta x \Delta p \approx \frac{h}{2}$$

This formula represents **Heisenberg's uncertainty principle**. Note that the value of the product, $\frac{h}{2}$ (representing the shaded areas of the graphs in Figure 14.26), is constant. The symbol $\approx$ means that $\Delta x \Delta p$ is approximately $\frac{h}{2}$. A more sophisticated argument produces the following expression:

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

Heisenberg's uncertainty principle: It is impossible to know both the position and momentum of a particle with unlimited precision at the same time.

This version is a common form of Heisenberg's uncertainty principle. It tells you that the uncertainty in your knowledge of both the position and momentum of a particle must always be greater than some small, but non-zero, value. You can never know both of these quantities with certainty at the same time! This result was very troubling to many physicists, including Albert Einstein, because it suggests that, at the level of atoms and particles, the universe is governed by chance and the laws of probability.

De Broglie's matter-wave hypothesis and its confirmation by Davisson and Germer had an unsettling effect on physicists. Heisenberg's work represented a logical extension of these ideas and helped set the stage for the birth of modern quantum theory.

MINDS ON Physics and Certainty

Two physicists who were deeply troubled by de Broglie's, and especially Heisenberg's, work were Max Planck and Albert Einstein. Suggest why their reaction is ironic and why these discoveries were difficult for physicists to accept.

To help with your answer, consider the importance of precision in classical physics, and Einstein's famous quote concerning the uncertainty principle: "God does not play dice with the universe!"

14.4 Check and Reflect

Knowledge

1. What is the wavelength of an electron that is moving at 20 000 m/s?
2. Calculate the momentum of a 500-nm photon.
3. What is the uncertainty in momentum of a particle if you know its location to an uncertainty of 1.0 nm?
4. An electron is trapped within a sphere of diameter 2.5×10^{-12} m. What is the minimum uncertainty in the electron's momentum?

Applications

5. In your television set, an electron is accelerated through a potential difference of 21 000 V.
   (a) How much energy does the electron acquire?
   (b) What is the wavelength of an electron of this energy?
   Ignore relativistic effects.
6. If an electron and a proton each have the same velocity, how do their wavelengths compare? Express your answer numerically as a ratio.

Extensions

7. According to classical physics, all atomic motion should cease at absolute zero. Is this state possible, according to quantum physics?
8. Derive the expression $E_n = \frac{n^2h^2}{8ml^2}$, $n = 1, 2, 3, \ldots$ for the energy of a particle in a box, where m is the mass of the particle, l is the length of the box, and n is one of the possible quantum states. (Hint: Remember that the wavelength of the nth standing wave confined to a box of length l is $\lambda_n = \frac{2l}{n}$.)

e TEST

To check your understanding of matter waves and Heisenberg's uncertainty principle, follow the eTest links at www.pearsoned.ca/school/physicssource.

14.5 Coming to Terms with Wave-particle Duality and the Birth of Quantum Mechanics

These fifty years of conscious brooding have brought me no nearer to the question of "What are light quanta?" Nowadays every clod thinks he knows it, but he is mistaken.

Albert Einstein

The wave-particle duality represents a deep and troubling mystery. For some physicists, most notably Einstein, the duality was seen as a flaw in quantum theory itself. Others, including Bohr, learned to accept rather than understand the duality. In this section, we will opt to accept and work with the wave-particle duality.

14-4 QuickLab

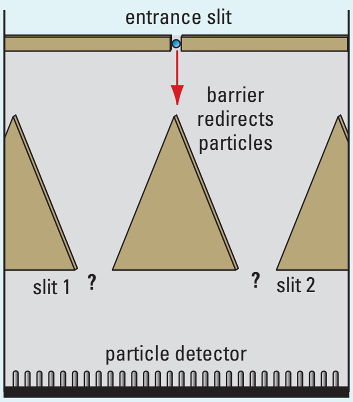
The Two-slit Interference Experiment with Particles

Problem

To investigate the pattern that a stream of particles produces when passing through a pair of thin slits

Materials

marble
two-slit apparatus (see Figure 14.27)
graph paper (or plot on spreadsheet)



◄ **Figure 14.27**

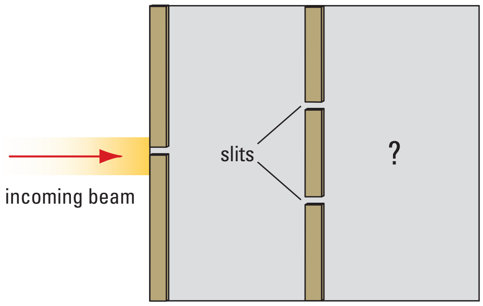
Procedure

1. Place the two-slit apparatus on a level table surface and incline it by a small angle to allow the marble to roll down. Repeat this process 100 times.
2. Record your observations by noting how many times the marble lands in each bin.
3. Graph the results of your experiment by plotting the bin number along the horizontal axis and the number of times the marble landed in a given bin on the vertical axis.

Questions

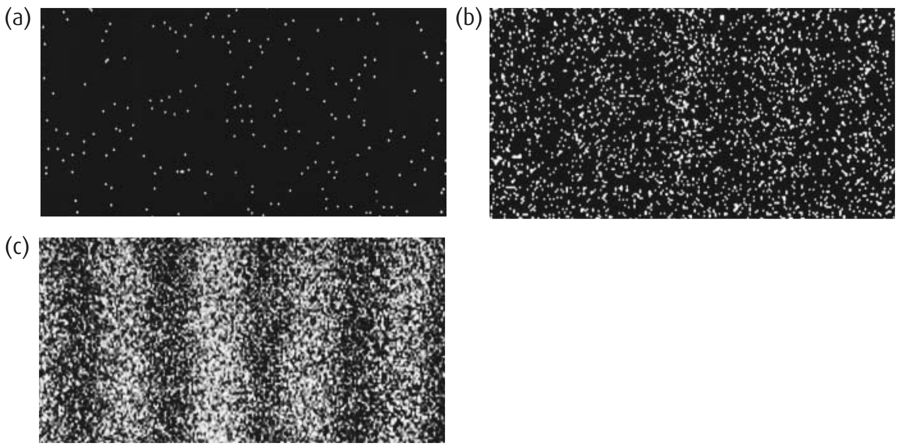
1. Why is it important that the table surface be level for this experiment?
2. For 100 trials, how many times would you expect the marble to pass through slit 1? Did you observe this result? Explain.
3. Where did the marble land most of the time? Did you expect this result? Explain.
4. Where would you expect the marble to be found least often? Do your data support your answer?
5. Would the results of your experiment be improved by combining the data from all of the lab groups in the class? Explain.

The wave-particle duality of light presents us with many puzzles and paradoxes. Consider, for example, the famous two-slit interference experiment that Thomas Young used in 1801 to convince most physicists that light was a wave (see Chapter 13). This time, however, you are going to put a modern, quantum mechanical twist on the experiment. Since you know that light can behave as a particle (photons) and that particles can behave as matter waves (electrons), it does not matter what you choose to "shine" through the slits. Let us choose light, but reduce its intensity by inserting a filter so that only one photon at a time can enter the box (Figure 14.28). Let the light slowly expose a photographic film or enter the detector of your digital camera.



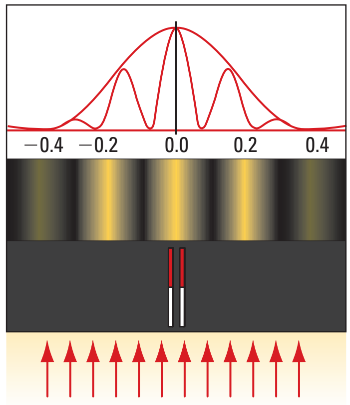
▲ **Figure 14.28** Young's double-slit experiment, modified such that the intensity of the beam entering the box is reduced to a level that allows only one photon at a time to enter

What will you observe? If you are impatient and let only a few photons through the slits, your result will be a random-looking scatter of dots where photons were absorbed by the film (Figure 14.29(a)). If you wait a little longer, the film will start to fill up (Figure 14.29(b)). Wait longer yet and something remarkable happens: You will see a two-slit interference pattern like the one in Figure 13.9 (Figure 14.29(c)). Why is this result so remarkable?

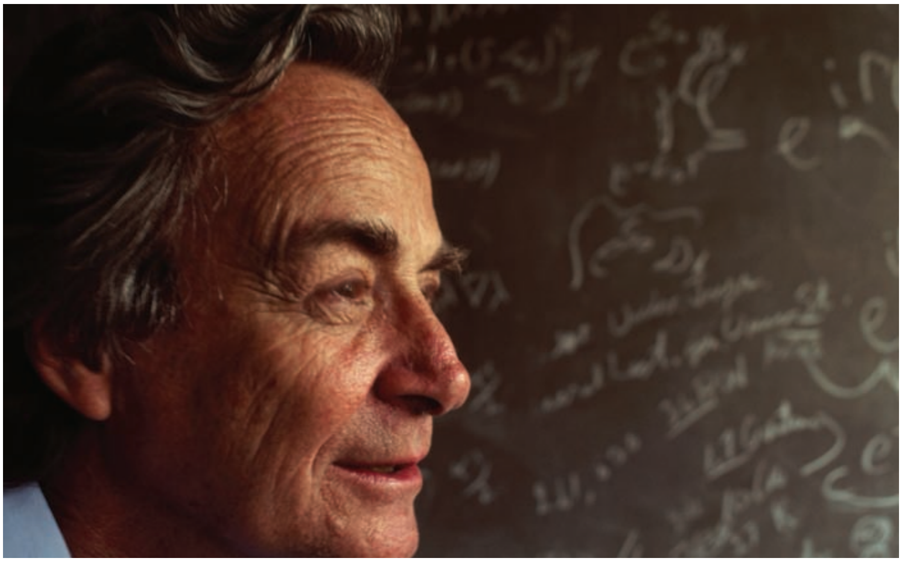


▶ **Figure 14.29** Three different results of the double-slit experiment. Image (a) shows the result of only a few photons being recorded. Image (b) shows the result of a few more photons, and image (c) shows the familiar double-slit interference pattern that forms when many photons are recorded.

If light was *only* a wave, then the explanation would be that waves from the top slit in Figure 14.28 were slightly out of phase with waves from the bottom slit in some locations, causing nodes to form. In other places, the waves would combine in phase to produce antinodes. You arranged, however, to have only one photon at a time enter the apparatus. So, the photon would either go through the top slit or the bottom slit. But even a photon cannot be in two different places at once! If the photons can only go through one slit (either the top or bottom one), why does a two-slit interference pattern, such as the one shown in Figure 14.30, result? Even though the individual photons go through only one slit, they somehow "know" that there is another slit open somewhere else! American physicist Richard Feynman (Figure 14.31) often used this example to emphasize how strange the quantum world is.



▲ **Figure 14.30** A two-slit interference pattern



▲ **Figure 14.31** Richard P. Feynman (1918–1988) was one of the founders of modern quantum theory. He once stated: "I think it is safe to say that no one understands quantum mechanics."

So what does it all mean? To try to understand the double-slit experiment as it applies to individual photons or electrons, it is useful to summarize the key points:

1. When the photon or electron is absorbed by the photographic film or the detector of your digital camera, it exhibits its *particle nature*.
2. The location where any one photon or electron is detected is random but distinct; that is, the photon or electron always arrives and is detected as a distinct particle.
3. Although the location of individual photons or electrons is random, the combined pattern that many photons form is the characteristic pattern of antinodes and nodes, as shown in Figure 14.30. This pattern shows the *wave nature* of the photons or electrons.

By the late 1920s, scientists developed a bold new interpretation of events. The wave-particle duality was showing that, at the level of atoms and molecules, the world was governed by the laws of probability and statistics. Although you cannot say much about what any one electron, for example, would do, you can make very precise predictions about the behaviour of very large numbers of electrons. In 1926, German physicist Max Born suggested that the *wave nature* of particles is best understood as a measure of the probability that the particle will be found at a particular location. The antinodes in the double-slit interference pattern exist because the particles have a high probability of being found at those locations after they pass through the double-slit apparatus. This measure of probability of a particle's

quantum indeterminacy: the probability of finding a particle at a particular location in a double-slit interference pattern

location is called **quantum indeterminacy**. This concept is the most profound difference between quantum physics and classical physics. According to quantum physics, nature does not always do exactly the same thing for the same set of conditions. Instead, the future develops probabilistically, and quantum physics is the science that allows you to predict the possible range of events that may occur.

Although you may think that quantum behaviour is remote and has nothing to do with your life, nothing could be further from the truth. As you will see in the next three chapters, quantum theory has become one of the most powerful scientific theories ever developed. Virtually all of the electronic equipment we use daily that improves our quality of life, and most of our current medical technologies and understanding, are possible because of the deep insights that quantum theory provides.

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American physicist and Nobel laureate Leon Lederman estimates that quantum physics is an essential part of the technologies responsible for over 25% of the North American gross national product.

14.5 Check and Reflect

Knowledge

1. Explain which of the following choices is the best one.
   (a) The double-slit experiment demonstrates that light is a wave.
   (b) The double-slit experiment shows that light is a particle.
   (c) The double-slit experiment illustrates that light has both wave and particle characteristics.
2. True or false? Explain.
   (a) The results of the double-slit experiment described in this section apply only to photons.
   (b) The results of the double-slit experiment apply to photons as well as to particles such as electrons.

Applications

3. Which of the following examples illustrates the wave nature of a quantum, and which illustrates the particle nature?
   (a) Electrons hit a phosphor screen and create a flash of light.
   (b) Electrons scatter off a crystal surface and produce a series of nodes and antinodes.
   (c) Light hits a photocell and causes the emission of electrons.

Extension

4. Imagine that, one night as you slept, Planck's constant changed from 6.63×10^{-34} J·s to 6.63 J·s. Explain, from a quantum mechanical point of view, why walking through the doorway of your bedroom could be a dangerous thing to do.

e TEST

To check your understanding of quantum mechanics, follow the eTest links at www.pearsoned.ca/school/physicssource.

CHAPTER 14 SUMMARY

Key Terms and Concepts

incandescent
blackbody radiation curve
blackbody
quantum
Planck's formula
quantized
photon
photoelectric effect
photoelectron
threshold frequency
work function
stopping potential
Compton scattering
Compton effect
wave-particle duality
Heisenberg's uncertainty principle
quantum indeterminacy

Key Equations

$$E = nhf$$

$$hf = W + E_k$$

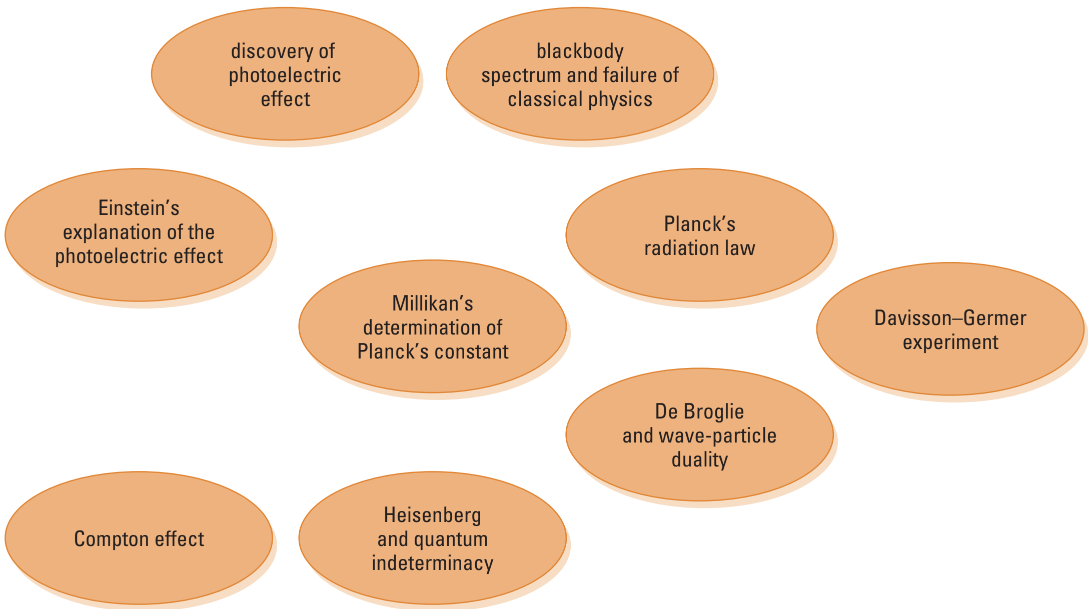
$$E_{k_{max}} = qV_{stopping}$$

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

$$\Delta\lambda = \lambda_f - \lambda_i = \frac{h}{mc}(1 - \cos\theta)$$

Conceptual Overview

Summarize this chapter by copying and completing the following concept map.



CHAPTER 14 REVIEW

Knowledge

1. (14.1) Explain what is meant by the term "ultraviolet catastrophe."

2. (14.1) Write the equation for Planck's formula and briefly explain what it means.

3. (14.1) What is the energy of a 450-nm photon? Express the answer in both joules and electron volts.

4. (14.1) If an X-ray photon has a wavelength 100 times smaller than the wavelength of a visible light photon, how do the energies of the two photons compare? Give a numerical answer.

5. (14.2) Who is credited with discovering the photoelectric effect?

6. (14.2) Who provided the correct explanation of the photoelectric effect? In what way(s) was this explanation radical when first proposed?

7. (14.2) If the threshold frequency for photoemission from a metal surface is 6.0×10^{14} Hz, what is the work function of the metal?

8. (14.3) Explain why the Compton effect provides critical evidence for the particle model of light.

9. (14.3) If a 0.010-nm photon scatters 90° after striking an electron, determine the change in wavelength ($\Delta\lambda$) for the photon.

10. (14.4) What is the wavelength of an electron that has a momentum of 9.1×10^{-27} N·s?

11. (14.4) What is the momentum of a 100-nm UV photon?

12. (14.4) If a particle is confined to a region in space 10 fm across, could the particle also be at rest? Explain, using Heisenberg's uncertainty principle.

Applications

13. How many photons are emitted each second by a 1.0-W flashlight? Use 600 nm as the average wavelength of the photons.

14. A beam of 300-nm photons is absorbed by a metal surface with work function 1.88 eV. Calculate the maximum kinetic energy of the electrons emitted from the surface.

15. Modern transmission electron microscopes can accelerate electrons through a 100-V potential difference and use these electrons to produce images of specimens. What is the wavelength of a 100-keV electron? Ignore relativistic effects. Why are electron microscopes capable of much higher magnification than light microscopes?

16. A major league baseball pitcher can throw a 40-m/s fastball of mass 0.15 kg.
(a) Calculate the wavelength of the ball.
(b) Why can you safely ignore quantum effects in this case?

17. Imagine that you are 100 m from a 100-W incandescent light bulb. If the diameter of your pupil is 2 mm, estimate how many photons enter your eye each second. (Note: You will need to make estimates and provide additional information.)

18. How many photons are emitted each second by an FM radio station whose transmitted power is 200 kW and whose frequency is 90.9 MHz?

19. An electron is trapped in a box that is 0.85 nm long. Calculate the three lowest energies that this electron can have. Why can the electron not have energy values between the values you calculated?

20. Calculate the momentum of a 100-keV X-ray photon.

Extensions

21. Argue that photons exert pressure. (Hint: Newton's second law, $F = ma$, can also be written as $F = \frac{\Delta p}{\Delta t}$. In other words, force is a measure of the rate of change in momentum with respect to time. Also, remember that pressure is defined as force acting over an area: $P = \frac{F}{A}$.)

22. After you graduate from university, you take a job in a patent office, assessing the feasibility of inventions. Your boss hands you a file and skeptically tells you it is from a physicist who claims that a 1.0-km^2 sail made from highly reflecting Mylar film could produce about 10 N of force simply by reflecting sunlight. You are asked to check the physics. Do the following:
    (a) Estimate how many photons arrive from the Sun per second per square metre at a distance equal to the Earth-Sun separation. You know that the top of Earth's atmosphere gets 1.4 kW/m^2 of energy from the Sun.
    (b) Calculate the momentum of each photon and remember that the photons are reflected.
    (c) Multiply the pressure (force per unit area) by the total area of the sail.

    Does the physicist's claim make sense?

23. How many photons per second does your radio respond to? Consider receiving a 100-MHz radio signal. The antenna in an average radio receiver must be able to move a current of at least 1.0 μA through a 10-mV potential difference in order to be detectable.

24. Einstein thought there was a fundamental flaw in quantum physics because "God does not play dice."
    (a) What do you think he meant by this statement? What part of quantum theory was Einstein referring to?
    (b) Why is it ironic that Einstein made this statement?

Consolidate Your Understanding

1. Describe two significant failings of classical physics that challenged physics prior to 1900.
2. Provide evidence for quantization of energy, and explain this concept to a friend.
3. List and describe at least two crucial experimental findings that support Einstein's claim that light has a particle nature.
4. Explain why it is incorrect to state that light is either a wave or a particle. Comment on how quantum physics tries to resolve this duality.
5. What is meant by the term "quantum indeterminacy"? Provide experimental evidence for this idea.

Think About It

Review your answers to the Think About It questions on page 703. How would you answer each question now?

eTEST

To check your understanding of the wave-particle duality of light, follow the eTest links at www.pearsoned.ca/school/physicssource.

From Particle to Quantum — How did we arrive at our present understanding of light?

Scenario

In the past 500 years, our understanding of the nature of electromagnetic radiation has grown immensely, from the particle vs. wave controversy between Newton and Huygens, to the strange wave-particle duality described by de Broglie's hypothesis, and to Heisenberg's uncertainty principle. The key evidence and theories along the way have opened up a bounty of applications, from fibre-optic communication networks, to scanning and tunnelling electron microscopes. With our understanding of electromagnetic radiation has come a vast wealth of information and new technologies, which in turn, have furthered our ability to probe and investigate the nature of our universe. From humble beginnings with simple lenses, the scientific community has followed a long and difficult pathway to our present understanding. In this project, you will retrace this pathway, highlighting the theories, evidence, and experiments that have contributed to our present understanding of light and electromagnetic radiation.

Planning

Working in small groups or individually, prepare a presentation that summarizes the intellectual journey from the earliest theories of the particle nature of light, to the more modern theory of wave-particle duality. Your presentation should include simulations and illustrations that identify key experimental evidence, and descriptions of each model and theory, including the scientists who proposed them.

Your summary can be presented in chronological order, from early discoveries, to later ones, or it can be organized around models (particle, wave, quantum, wave-particle duality).

Materials

text and Internet resources
simulations, illustrations, photos of evidence collected in experiments
presentation software (PowerPoint, html editor, etc.)

Assessing Results

Assess the success of your project based on a rubric* designed in class that considers:

- research strategies
- completeness of evidence and effectiveness of presentation

Procedure

1. Define each of the following models: particle, wave, quantum, and wave-particle duality.
2. Identify each of the scientists involved with each model.
3. Using either a table or a timeline, place each model and the related scientists in order from earliest, to most recent.
4. On your table or a timeline, identify each key experiment and the evidence that was used to support each model. Include the following experimental evidence and theories:
   - reflection, refraction, dispersion, diffraction, interference, polarization, blackbody radiation, photoelectric effect, Compton effect, de Broglie's hypothesis, and Heisenberg's uncertainty principle
5. Use your table or timeline as the basis for preparing your presentation. Use simulations, illustrations, and photographs where possible to describe experimental evidence.

Thinking Further

The evolution of an idea or theory can take place over hundreds of years, with one participant handing off evidence to the next participant. A sort of relay develops, because the race is simply too long for one person to complete alone. With this in mind, consider the following questions that could be answered at the end of your presentation.

- A relay race has an end. Is there an end in the race to fully understand the nature of electromagnetic radiation and light?
- If the relay is not over, where do you think we are going from here?
- How have we used the knowledge of our predecessors in determining where to look next? Explain.

*Note: Your instructor will assess the project using a similar assessment rubric.

UNIT VII SUMMARY

Unit Concepts and Skills: Quick Reference

Concepts	Summary	Resources and Skill Building
Chapter 13	**The wave model can be used to describe the characteristics of electromagnetic radiation.**	
	13.1 What Is Electromagnetic Radiation?	
Types of electromagnetic radiation	Frequency, wavelength, and source are used to identify types of EMR.	Figure 13.4; Table 13.1
Models of EMR	Different models were used to explain the behaviour of EMR.	Figures 13.5–13.9
Maxwell's electromagnetic theory	Maxwell's theory linked concepts of electricity and magnetism.	Figures 13.10–13.15
	Electromagnetic radiation is produced by accelerating charges.	Figures 13.16-13.19; Minds On: Going Wireless
	13.2 The Speed of Electromagnetic Radiation	
Speed of electromagnetic radiation	Galileo, Roemer and Huygens, and Fizeau measured the speed of EMR, but Michelson's experiment made the definitive measurement.	Figures 13.21-13.24; Example 13.1; 13-2 QuickLab
	13.3 Reflection	
The Law of Reflection, image formation, and ray diagrams	The angle of reflection equals the angle of incidence and is in the same plane. Ray diagrams show a light ray interacting with a surface. Three rays predict the location and characteristics of the image.	Figures 13.28-13.30; 13-3 QuickLab; Minds On: Image in a Mirror; Figures 13.31–13.32; Figures 13.36–13.39; 13-4 QuickLab
Image formation/equations	The mirror equation relates the focal length of a curved mirror to the image and object distances.	13-5 Problem-Solving Lab; Example 13.2
	13.4 Refraction	
Refraction and Snell's Law	Snell's Law relates the refraction of a light wave to the speed with which light travels in different media.	Table 13.4; Examples 13.3–13.4; 13-6 Inquiry Lab
Total internal reflection	All light is internally reflected at an interface if the angle of refraction is 90° or greater.	Figures 13.49-13.53; Example 13.5, 13-7 Decision-Making Analysis
Dispersion and recomposition	White light can be separated into its component wavelengths.	Figures 13.54–13.56; Table 13.5; 13-8 QuickLab
Image formation with thin lenses	The lens equation relates the focal length of a curved lens to the image and object distances.	Figures 13.57–13.59; Example 13.6; Figure 13.61; Example 13.7; 13-9 Inquiry Lab
	13.5 Diffraction and Interference	
Huygens' Principle	Huygens predicted the motion of a wave front as many point sources.	Figures 13.67–13.69
Young's experiment, interference, and diffraction	Young's experiment showed that two beams of light produce an interference pattern and that light behaves as a wave.	Figures 13.70–13.78; Examples 13.8–13.9 Figure 13.80
Diffraction gratings	Light on a multi-slit diffraction grating produces an interference pattern.	Figure 13.81; Example 13.10; 13-10 Inquiry Lab
Polarization	EMR absorption by polarizing filters supports the wave model of light.	13-1 QuickLab; Figure 13.86; Figures 13.88–13.90
Chapter 14	**The wave–particle duality reminds us that sometimes truth really *is* stranger than fiction!**	
	14.1 The Birth of the Quantum	
Quantum	Classical physics was unable to explain the shape of the blackbody radiation curve.	14-1 QuickLab, Figures 14.3–14.4
	A quantum is the smallest amount of energy of a particular wavelength or frequency that a body can absorb, given by $E = hf$.	Examples 14.1, 14.2, 14.3; Minds On: What's Wrong with This Analogy? Figure 14.6
	14.2 The Photoelectric Effect	
Photoelectric effect	The work function is the minimum energy required to cause photoemission of electrons from a metal surface.	14-2 QuickLab, Table 14.1
Planck's constant	Millikan's photoelectric experiment provided a way to measure Planck's constant. The photoelectric effect obeys the law of conservation of energy.	Figure 14.12, 14-3 Design a Lab; Examples 14.5–14.6
	14.3 The Compton Effect	
Compton effect	When an electron scatters an X ray, the change in the X ray's wavelength relates to the angle of the X-ray photon's scattering.	Figure 14.16; Examples 14.7–14.8
	14.4 Matter Waves and the Power of Symmetric Thinking	
Wave–particle duality	Something that has momentum also has wavelength: Particles can act like waves.	Examples 14.9–14.10
Heisenberg's uncertainty principle	Particles have a wave nature, so it is impossible to precisely know their position at the same time as their momentum.	Figures 14.21, 14.22, 14.24, 14.26; Example 14.11
	14.5 Coming to Terms with Wave–particle Duality and the Birth of Quantum Mechanics	
Quantum indeterminacy	Wave-particle duality illustrates the probabilistic nature of atoms and molecules. Quantum indeterminacy is the measure of the probability of a particle's location.	14-4 QuickLab, Figures 14.28–14.30

UNIT VII REVIEW

Vocabulary

1. Use your own words to define these terms:
   angle of diffraction
   blackbody
   blackbody radiation curve
   Compton effect
   Compton scattering
   converging
   critical angle
   diffraction
   diffraction grating
   dispersion
   diverging
   electromagnetic radiation
   focal point
   frequency
   Heisenberg's uncertainty principle
   Huygens' Principle
   image attitude
   incandescent
   interference
   law of reflection
   magnification
   node, antinode
   particle model
   path length
   period
   photoelectric effect
   photoelectrons
   photon
   Planck's formula
   polarization
   quantized
   quantum
   quantum indeterminacy
   refraction
   refractive index
   Snell's Law
   spectrum
   stopping potential
   threshold frequency
   total internal reflection
   wave model
   wave-particle duality
   wavelength
   work function

Knowledge

CHAPTER 13

2. How does the quantum model reconcile the wave model and the particle model of light?
3. How did Maxwell's work with capacitors influence his theories on electromagnetism?
4. Describe the experimental evidence that supports all of Maxwell's predictions about electromagnetic radiation.
5. Discuss the significance of the word "changing" in Maxwell's original description of electromagnetic radiation.
6. Why does a spark produce electromagnetic radiation?
7. If a metal conductor, such as a spoon, is placed in an operating microwave oven, a spark is produced. Why?
8. Using a ray diagram, show three rays that are needed to identify and verify the characteristics of an image.
9. What is the relationship between the focal length and the radius of curvature for a curved mirror?
10. What is a virtual focal point and how is it different from a real focal point?
11. Explain, using a ray diagram, how a real image can be formed when using two concave mirrors.
12. When you place the concave side of a spoon on your nose and slowly pull it away from your face, your image disappears at a certain distance. What is the significance of this distance?
13. When an object such as a paddle is partially submerged in water, why does it appear bent?
14. Explain how Snell's Law supports the wave theory of light.
15. What happens to the wavelength of monochromatic light when it passes from air into water?
16. Several people holding hands run down the beach and enter the water at an angle. Explain what happens to the speed and direction of the people as they enter the water.
17. How was Newton able to show that a prism separates the colours in the spectrum, rather than adding the colours to white light?

18. What is Huygens' Principle?

19. A straight wave front is incident on a barrier with a small hole. Using a diagram, describe the shape of the wave front a moment after it makes contact with the barrier.

20. Using a schematic, illustrate Young's experiment.

21. Explain why diffraction supports the wave model of light.

22. What key evidence was observed by Dominique Arago in 1818? Why was this evidence crucial to the acceptance of the wave model of light?

23. How must two plane polarizing filters be aligned in order to fully block electromagnetic radiation?

24. Is an electromagnetic wave one-dimensional, two-dimensional, or three-dimensional? Explain.

CHAPTER 14

25. Is a quantum of blue light the same as a quantum of red light? Explain.

26. How much energy is carried by a photon of wavelength 550 nm?

27. Explain how you can estimate the surface temperature of a star by noting its colour.

28. Arrange the following photons from highest to lowest energy: ultraviolet photon, 10-nm photon, microwave photon, gamma-ray photon, 600-nm photon, infrared photon.

29. What is the frequency of blue light of wavelength 500 nm?

30. Ultraviolet light causes sunburn whereas visible light does not. Explain, using Planck's formula.

31. Explain what is meant by the term "threshold frequency."

32. How does the energy of photoelectrons emitted by a metal change as the intensity of light hitting the metal surface changes?

33. What is the maximum wavelength of light that will cause photoemission from a metal having a work function of 3.2 eV?

34. Explain the difference between the Compton effect and the photoelectric effect.

35. What is meant by the term "wave-particle duality"?

36. Even though photons have no mass, they still carry momentum. What is the momentum of a 300-nm ultraviolet photon?

37. What is the de Broglie wavelength of an electron moving at 3000 km/s?

38. A proton and a neutron are both moving at the same speed. Which particle has the shorter de Broglie wavelength?

39. Explain, using wave mechanics, why it is impossible for a particle to have zero kinetic energy when it is confined to a fixed region in space.

Applications

40. If visible light is a particle, predict what would be observed if light passed through two small holes in a barrier. Compare this prediction to what is actually observed when light passes through two small holes in a barrier. What does this suggest about the nature of light?

41. How many radio-frequency photons are emitted each second by a radio station that broadcasts at a frequency of 90.9 MHz and has a radiated power of 50 kW?

42. Explain how an antenna is able to "sense" electromagnetic radiation.

43. Detailed measurements of the Moon's orbit could be calculated after the Apollo mission placed large reflecting mirrors on the surface of the Moon. If a laser beam were directed at the mirrors on the Moon and the light was reflected back to Earth in 2.56 s, how far away, in kilometres, is the Moon?

44. When you increase the intensity of a green light, do you change the energy of the green-light photons? Why does the light get brighter?

45. A Michelson apparatus is used to obtain a value of 2.97×10^8 m/s for the speed of light. The sixteen-sided rotating mirror completes 1.15×10^4 revolutions in one minute. How far away was the flat reflecting mirror?

46. An eight-sided mirror like Michelson's is set up. The light reflects from the rotating mirror and travels to a fixed mirror 5.00 km away. If the rotating mirror turns through one-eighth of a rotation before the light returns from the fixed mirror, what is the rate of rotation?

47. A sixteen-sided mirror rotates at 4.50×10^2 Hz. How long does it take to make one-sixteenth of a rotation?

48. Why do police and search-and-rescue agencies use infrared cameras for night-time surveillance when looking for people? Explain why infrared is used and not some other part of the electromagnetic spectrum.

49. The speed of light in a material is determined to be 1.24×10^8 m/s. What is the material?

50. Light of wavelength 520 nm strikes a metal surface having a work function of 2.3 eV. Will the surface emit photoelectrons?

51. A student replicating Michelson's experiment uses an eight-sided mirror and a fixed mirror located 35.0 km away. Light is reflected through the system when the rotating mirror turns at 5.20×10^2 Hz. What is the experimentally determined speed of light and the percentage error in the measurement?

52. An electrically neutral 1-m^2 piece of aluminium is put in orbit high above Earth. Explain why, after a period of time, the piece of aluminium will become electrically charged. Predict the sign of the charge.

53. An object is located in front of a diverging mirror with a focal length of 5.0 cm. If the virtual image is formed 3.0 cm from the vertex of the mirror and is 1.0 cm high, determine the object's characteristics and position.

54. Photon A has four times the energy of photon B. Compare the wavelengths and the momenta of the two photons.

55. A light ray passes from water into ruby at an angle of 10°. What is the angle of refraction?

56. An X-ray photon of wavelength 0.025 nm collides elastically with an electron and scatters through an angle of 90°. How much energy did the electron acquire in this collision and in what important way did the X ray change?

57. A 3.0-cm-high object is placed 10.0 cm from a converging lens with a focal length of 5.0 cm. Using the thin lens equation, determine the image attributes and position.

58. Imagine that you are asked to review a patent application for a laser-powered deep space probe. The proposal you are reviewing calls for a 1-kW laser producing 500-nm photons. The total mass of the spacecraft, including the laser, is 1000 kg. Determine
   (a) if laser propulsion is possible, and the underlying principle of this form of propulsion.
   (b) how fast the spacecraft would be travelling after one year of "laser-drive" if it started from rest.

59. List two ways to recompose the spectrum into white light.

60. Calculate the wavelength of electrons used in a transmission electron microscope if the electrons are accelerated through an electric field of potential 75 kV. Ignore relativistic effects.

61. In an experiment similar to Young's, two waves arrive at the screen one half-wavelength out of phase. What will be observed at this point on the screen?

62. What is the minimum or rest energy of an electron confined to a one-dimensional box 1 nm long?

63. A mixture of violet light ($\lambda = 420$ nm) and red light ($\lambda = 650$ nm) are incident on a diffraction grating with 1.00×10^4 lines/cm. For each wavelength, determine the angle of deviation that leads to the first antinode.

64. Light with a wavelength of 700 nm is directed at a diffraction grating with 1.50×10^2 slits/cm. What is the separation between adjacent antinodes when the screen is located 2.50 m away?

65. Your physics teacher, eager to get to class, was observed from a police spotting-plane to travel a distance of 222 m in 10 s. The speed limit was 60 km/h, and you can quickly determine that he was speeding. The police issued a ticket, but your teacher decided to argue the case, citing Heisenberg's uncertainty principle as his defence. He argued that the speed of his car was fundamentally uncertain and that he was not speeding. Explain how you would use Heisenberg's uncertainty principle in this case and comment on whether your teacher's defence was good. The combined mass of the car and your teacher is 2000 kg.

Extensions

66. Traditional radio technology blends a carrier signal and an audio signal with either frequency or amplitude modulation. This generates a signal with two layers of information—one for tuning and one containing the audio information. Describe the two layers of information that a cell phone signal must contain in order to establish and maintain constant communication with a cell phone network.

67. Use Heisenberg's uncertainty principle to estimate the momentum and kinetic energy of an electron in a hydrogen atom. Express the energy in electron volts. The hydrogen atom can be approximated by a square with 0.2-nm sides. (Hint: Kinetic energy is related to momentum via the equation $E_k = \frac{p^2}{2m}$.)

68. Global positioning satellites maintain an orbital altitude of 20 000 km. How long does it take for a time signal to travel from the satellite to a receiver located directly below the satellite?

69. Why do some metals have a higher threshold frequency than others? How is this phenomenon related to electric fields?

70. Explain how an optical fibre is able to transmit a light pulse over a long distance without a loss in intensity.

71. The human eye can detect as few as 500 photons of light, but in order to see, this response needs to occur over a prolonged period of time. Seeing requires approximately 10 000 photons per second. If the Sun emits 3.9×10^{26} W, mostly in the blue-green part of the spectrum, and if roughly half of the energy is emitted as visible light, estimate how far away a star like our Sun would be visible.

72. A beam of 200-eV electrons is made to pass through two slits in a metal film that are separated by 50 nm. A phosphor screen is placed 1 m behind the slits. Sketch what you would expect to see. Provide calculations to support your answer.

Skills Practice

73. An object is located 25.0 cm from a diverging mirror with a focal length of 10.0 cm. Draw a ray diagram to scale to determine the following:
   (a) the image location and type
   (b) the image attitude
   (c) the magnification of the image

74. The following data are taken from an experiment in which the maximum kinetic energy of photoelectrons is related to the wavelength of the photons hitting a metal surface. Use these data to produce a graph that shows the energy of the incident photons on the horizontal axis and the kinetic energy of photoelectrons on the vertical axis. From this graph, determine the work function for the metal.

Wavelength (nm)	Kinetic Energy (eV)
200	3.72
250	2.47
300	1.64
350	1.05
400	0.61
450	0.26

75. Use a ray diagram to show why a double convex lens is called a converging lens and a double concave lens is called a diverging lens. Label the principal axis, principal focus, secondary focus, and optical centre.

76. Calculate the momentum and wavelength of an electron that has a kinetic energy of 50 keV. Ignore relativistic effects.

77. Explain, with the aid of a ray diagram, why an image does not form when you place an object at the focal point of a converging lens.

78. Determine the momentum of an X ray of wavelength 10 nm.

79. Prepare a table in which you compare the wave and particle models of light. List as many phenomena as you can think of and decide whether light can be explained best using the wave or the particle model. How would you answer the question, "Is light a wave or a particle?"

Self-assessment

80. Describe to a classmate which concepts of electromagnetic radiation you found most interesting when studying this unit. Give reasons for your choices.

81. Identify one issue pertaining to the wave-particle duality of light that you would like to investigate in greater detail.

82. What concept in this unit did you find most difficult? What steps could you take to improve your understanding?

eTEST

To check your understanding of electromagnetic radiation and the dual nature of light, follow the eTest links at www.pearsoned.ca/school/physicssource.