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Phys-ics

HIGH SCHOOL

CHAPTER 19
Electrical Circuits

Figure 19.1 Electric energy in massive quantities is transmitted from this hydroelectric facility, the Srisailam power station located along the Krishna River in India, by the movement of charge—that is, by electric current. (credit: Chintohere, Wikimedia Commons)

Chapter Outline

19.1 Ohm's law

19.2 Series Circuits

19.3 Parallel Circuits

19.4 Electric Power

INTRODUCTION The flicker of numbers on a handheld calculator, nerve impulses carrying signals of vision to the brain, an ultrasound device sending a signal to a computer screen, the brain sending a message for a baby to twitch its toes, an electric train pulling into a station, a hydroelectric plant sending energy to metropolitan and rural users—these and many other examples of electricity involve electric current, which is the movement of charge. Humanity has harnessed electricity, the basis of this technology, to improve our quality of life. Whereas the previous chapter concentrated on static electricity and the fundamental force underlying its behavior, the next two chapters will be devoted to electric and magnetic phenomena involving current. In addition to exploring applications of electricity, we shall gain new insights into the workings of nature.

19.1 Ohm's law

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe how current is related to charge and time, and distinguish between direct current and alternating current
- Define resistance and verbally describe Ohm's law
- Calculate current and solve problems involving Ohm's law

Section Key Terms

alternating current	ampere	conventional current	direct current	electric current
nonohmic	ohmic	Ohm's law	resistance	

Direct and Alternating Current

Just as water flows from high to low elevation, electrons that are free to move will travel from a place with low potential to a place with high potential. A battery has two terminals that are at different potentials. If the terminals are connected by a conducting wire, an electric current (charges) will flow, as shown in Figure 19.2. Electrons will then move from the low-potential terminal of the battery (the *negative* end) through the wire and enter the high-potential terminal of the battery (the *positive* end).

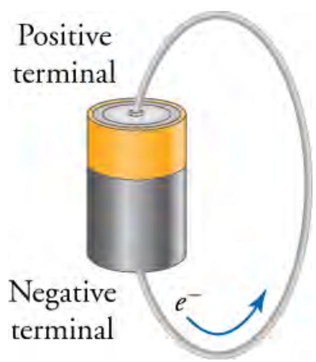


Figure 19.2 A battery has a wire connecting the positive and negative terminals, which allows electrons to move from the negative terminal to the positive terminal.

Electric current is the rate at which electric charge moves. A large current, such as that used to start a truck engine, moves a large amount very quickly, whereas a small current, such as that used to operate a hand-held calculator, moves a small amount of charge more slowly. In equation form, electric current I is defined as

$$I = \frac{\Delta Q}{\Delta t}$$

where ΔQ is the amount of charge that flows past a given area and Δt is the time it takes for the charge to move past the area. The SI unit for electric current is the ampere (A), which is named in honor of the French physicist André-Marie Ampère (1775–1836). One **ampere** is one coulomb per second, or

$$1 \text{ A} = 1 \text{ C/s}.$$

Electric current moving through a wire is in many ways similar to water current moving through a pipe. To define the flow of water through a pipe, we can count the water molecules that flow past a given section of the pipe. As shown in Figure 19.3, electric current is very similar. We count the number of electrical charges that flow past a section of a conductor; in this case, a wire.

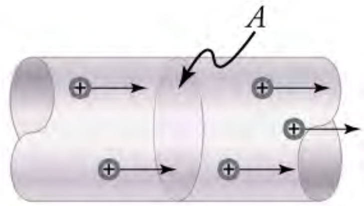


Figure 19.3 The electric current moving through this wire is the charge that moves past the cross-section A divided by the time it takes for this charge to move past the section *A*.

Assume each particle q in Figure 19.3 carries a charge $q = 1\ \text{nC}$, in which case the total charge shown would be $\Delta Q = 5q = 5\ \text{nC}$. If these charges move past the area A in a time $\Delta t = 1\ \text{ns}$, then the current would be

$$I = \frac{\Delta Q}{\Delta t} = \frac{5\ \text{nC}}{1\ \text{ns}} = 5\ \text{A}. \tag{19.1}$$

Note that we assigned a positive charge to the charges in Figure 19.3. Normally, negative charges—electrons—are the mobile charge in wires, as indicated in Figure 19.2. Positive charges are normally stuck in place in solids and cannot move freely. However, because a positive current moving to the right is the same as a negative current of equal magnitude moving to the left, as shown in Figure 19.4, we define **conventional current** to flow in the direction that a positive charge would flow if it could move. Thus, unless otherwise specified, an electric current is assumed to be composed of positive charges.

Also note that one Coulomb is a significant amount of electric charge, so 5 A is a very large current. Most often you will see current on the order of milliamperes (mA).

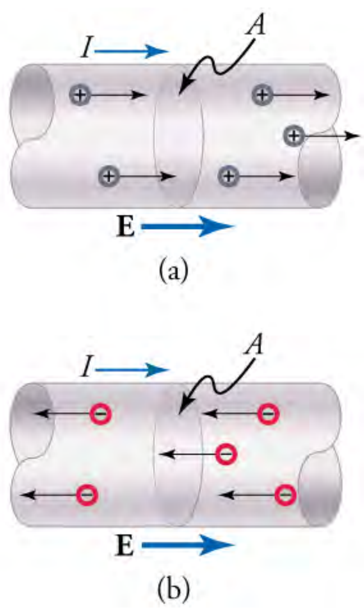


Figure 19.4 (a) The electric field points to the right, the current moves to the right, and positive charges move to the right. (b) The equivalent situation but with negative charges moving to the left. The electric field and the current are still to the right.

Snap Lab

Vegetable Current

This lab helps students understand how current works. Given that particles confined in a pipe cannot occupy the same space, pushing more particles into one end of the pipe will force the same number of particles out of the opposite end. This creates a current of particles.

Find a straw and dried peas that can move freely in the straw. Place the straw flat on a table and fill the straw with peas. When you push one pea in at one end, a different pea should come out of the other end. This demonstration is a model for an electric current. Identify the part of the model that represents electrons and the part of the model that represents the supply of electrical energy. For a period of 30 s, count the number of peas you can push through the straw. When finished, calculate the *pea current* by dividing the number of peas by the time in seconds.

Note that the flow of peas is based on the peas physically bumping into each other; electrons push each other along due to mutually repulsive electrostatic forces.

GRASP CHECK

Suppose four peas per second pass through a straw. If each pea carried a charge of $1\ \text{nC}$, what would the electric current be through the straw?

a. The electric current would be the pea charge multiplied by $1\ \text{nC/pea}$.
b. The electric current would be the pea current calculated in the lab multiplied by $1\ \text{nC/pea}$.
c. The electric current would be the pea current calculated in the lab.
d. The electric current would be the pea charge divided by time.

The direction of conventional current *is the direction that positive charge would flow*. Depending on the situation, positive charges, negative charges, or both may move. In metal wires, as we have seen, current is carried by electrons, so the negative charges move. In ionic solutions, such as salt water, both positively charged and negatively charged ions move. This is also true in nerve cells. Pure positive currents are relatively rare but do occur. History credits American politician and scientist Benjamin Franklin with describing current as the direction that positive charges flow through a wire. He named the type of charge associated with electrons negative long before they were known to carry current in so many situations.

As electrons move through a metal wire, they encounter obstacles such as other electrons, atoms, impurities, etc. The electrons scatter from these obstacles, as depicted in Figure 19.5. Normally, the electrons lose energy with each interaction. [1] To keep the electrons moving thus requires a force, which is supplied by an electric field. The electric field in a wire points from the end of the wire at the higher potential to the end of the wire at the lower potential. Electrons, carrying a negative charge, move on average (or *drift*) in the direction opposite the electric field, as shown in Figure 19.5.

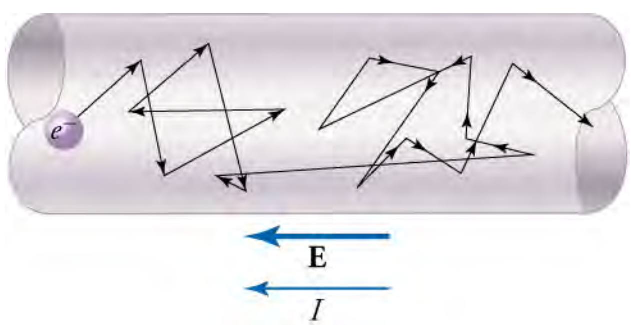


Figure 19.5 Free electrons moving in a conductor make many collisions with other electrons and atoms. The path of one electron is shown. The average velocity of free electrons is in the direction opposite to the electric field. The collisions normally transfer energy to the conductor, so a constant supply of energy is required to maintain a steady current.

So far, we have discussed current that moves constantly in a single direction. This is called **direct current**, because the electric charge flows in only one direction. Direct current is often called *DC* current.

Many sources of electrical power, such as the hydroelectric dam shown at the beginning of this chapter, produce **alternating current**, in which the current direction alternates back and forth. Alternating current is often called *AC current*. Alternating current moves back and forth at regular time intervals, as shown in Figure 19.6. The alternating current that comes from a normal wall socket does not suddenly switch directions. Rather, it increases smoothly up to a maximum current and then smoothly decreases back to zero. It then grows again, but in the opposite direction until it has reached the same maximum value. After that, it decreases smoothly back to zero, and the cycle starts over again.

1This energy is transferred to the wire and becomes thermal energy, which is what makes wires hot when they carry a lot of current.

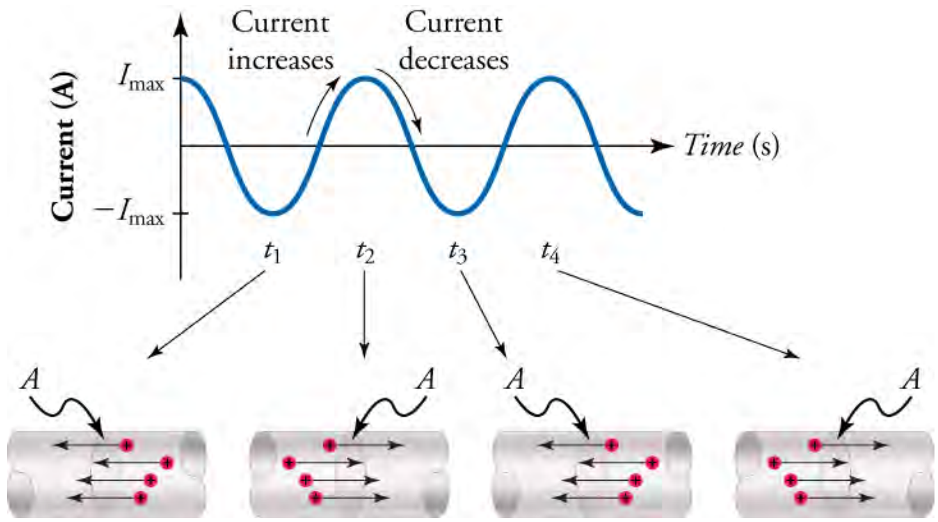


Figure 19.6 With alternating current, the direction of the current reverses at regular time intervals. The graph on the top shows the current versus time. The negative maxima correspond to the current moving to the left. The positive maxima correspond to current moving to the right. The current alternates regularly and smoothly between these two maxima.

Devices that use AC include vacuum cleaners, fans, power tools, hair dryers, and countless others. These devices obtain the power they require when you plug them into a wall socket. The wall socket is connected to the power grid that provides an alternating potential (AC potential). When your device is plugged in, the AC potential pushes charges back and forth in the circuit of the device, creating an alternating current.

Many devices, however, use DC, such as computers, cell phones, flashlights, and cars. One source of DC is a battery, which provides a constant potential (DC potential) between its terminals. With your device connected to a battery, the DC potential pushes charge in one direction through the circuit of your device, creating a DC current. Another way to produce DC current is by using a transformer, which converts AC potential to DC potential. Small transformers that you can plug into a wall socket are used to charge up your laptop, cell phone, or other electronic device. People generally call this a *charger* or a *battery*, but it is a transformer that transforms AC voltage into DC voltage. The next time someone asks to borrow your laptop charger, tell them that you don't have a laptop charger, but that they may borrow your converter.

WORKED EXAMPLE

Current in a Lightning Strike

A lightning strike can transfer as many as 10^{20} electrons from the cloud to the ground. If the strike lasts 2 ms, what is the average electric current in the lightning?

STRATEGY

Use the definition of current, $I = \frac{\Delta Q}{\Delta t}$. The charge ΔQ from 10^{20} electrons is $\Delta Q = ne$, where $n = 10^{20}$ is the number of electrons and $e = -1.60 \times 10^{-19}\,\text{C}$ is the charge on the electron. This gives

$$\Delta Q = 10^{20} \times \left(-1.60 \times 10^{-19}\,\text{C}\right) = -16.0\ \text{C}. \tag{19.2}$$

The time $\Delta t = 2 \times 10^{-3}\,\text{s}$ is the duration of the lightning strike.

Solution

The current in the lightning strike is

$$\begin{aligned} I &= \frac{\Delta Q}{\Delta t} \\ &= \frac{-16.0\ \text{C}}{2 \times 10^{-3}\,\text{s}} \\ &= -8\ \text{kA}. \end{aligned} \tag{19.3}$$

Discussion

The negative sign reflects the fact that electrons carry the negative charge. Thus, although the electrons flow from the cloud to the ground, the positive current is defined to flow from the ground to the cloud.

WORKED EXAMPLE

Average Current to Charge a Capacitor

In a circuit containing a capacitor and a resistor, it takes 1 min to charge a 16 µF capacitor by using a 9-V battery. What is the average current during this time?

STRATEGY

We can determine the charge on the capacitor by using the definition of capacitance: $C = \frac{Q}{V}$. When the capacitor is charged by a 9-V battery, the voltage across the capacitor will be $V = 9\ \text{V}$. This gives a charge of

$$\begin{aligned} C &= \frac{Q}{V} \\ Q &= CV. \end{aligned} \tag{19.4}$$

By inserting this expression for charge into the equation for current, $I = \frac{\Delta Q}{\Delta t}$, we can find the average current.

Solution

The average current is

$$\begin{aligned} I &= \frac{\Delta Q}{\Delta t} \\ &= \frac{CV}{\Delta t} \\ &= \frac{(16 \times 10^{-6}\text{F})(9\ \text{V})}{60\ \text{s}} \\ &= 2.4 \times 10^{-6}\text{A} \\ &= 2.4\ \mu\text{A}. \end{aligned} \tag{19.5}$$

Discussion

This small current is typical of the current encountered in circuits such as this.

Practice Problems

1. 10 nC of charge flows through a circuit in 3.0×10^{-6} s . What is the current during this time?
   a. The current passes through the circuit is 3.3×10^{-3} A.
   b. The current passes through the circuit is 30 A.
   c. The current passes through the circuit is 33 A.
   d. The current passes through the circuit is 0.3 A.

2. How long would it take a 10-mA current to charge a capacitor with 5.0 mC?
   a. 0.50 s
   b. 5 ns
   c. 0.50 ns
   d. 50 μs

Resistance and Ohm's Law

As mentioned previously, electrical current in a wire is in many ways similar to water flowing through a pipe. The water current that can flow through a pipe is affected by obstacles in the pipe, such as clogs and narrow sections in the pipe. These obstacles slow down the flow of current through the pipe. Similarly, electrical current in a wire can be slowed down by many factors, including impurities in the metal of the wire or collisions between the charges in the material. These factors create a resistance to the electrical current. **Resistance** is a description of how much a wire or other electrical component opposes the flow of charge through it. In the 19th century, the German physicist Georg Simon Ohm (1787–1854) found experimentally that current through a conductor is proportional to the voltage drop across a current-carrying conductor.

$$I \propto V$$

The constant of proportionality is the resistance R of the material, which leads to

$$V = IR(1.3).$$

This relationship is called **Ohm's law**. It can be viewed as a cause-and-effect relationship, with voltage being the cause and the current being the effect. Ohm's law is an empirical law like that for friction, which means that it is an experimentally observed phenomenon. The units of resistance are volts per ampere, or V/A. We call a V/A an *ohm*, which is represented by the uppercase Greek letter omega (Ω). Thus,

$$1\ \Omega = 1\ \text{V/A}(1.4).$$

Ohm's law holds for most materials and at common temperatures. At very low temperatures, resistance may drop to zero (superconductivity). At very high temperatures, the thermal motion of atoms in the material inhibits the flow of electrons, increasing the resistance. The many substances for which Ohm's law holds are called **ohmic**. Ohmic materials include good conductors like copper, aluminum, and silver, and some poor conductors under certain circumstances. The resistance of ohmic materials remains essentially the same for a wide range of voltage and current.

WATCH PHYSICS

Introduction to Electricity, Circuits, Current, and Resistance

This video presents Ohm's law and shows a simple electrical circuit. The speaker uses the analogy of pressure to describe how electric potential makes charge move. He refers to electric potential as *electric pressure*. Another way of thinking about electric potential is to imagine that lots of particles of the same sign are crowded in a small, confined space. Because these charges have the same sign (they are all positive or all negative), each charge repels the others around it. This means that lots of charges are constantly being pushed towards the outside of the space. A complete electric circuit is like opening a door in the small space: Whichever particles are pushed towards the door now have a way to escape. The higher the electric potential, the harder each particle pushes against the others.

GRASP CHECK

If, instead of a single resistor R, two resistors each with resistance R are drawn in the circuit diagram shown in the video, what can you say about the current through the circuit?

a. The amount of current through the circuit must decrease by half.
b. The amount of current through the circuit must increase by half.
c. The current must remain the same through the circuit.
d. The amount of current through the circuit would be doubled.

Virtual Physics

Ohm's Law

Click to view content (http://www.openstax.org/l/28ohms_law)

This simulation mimics a simple circuit with batteries providing the voltage source and a resistor connected across the batteries. See how the current is affected by modifying the resistance and/or the voltage. Note that the resistance is modeled as an element containing small *scattering centers*. These represent impurities or other obstacles that impede the passage of the current.

GRASP CHECK

In a circuit, if the resistance is left constant and the voltage is doubled (for example, from $3\ \text{V}$ to $6\ \text{V}$), how does the current change? Does this conform to Ohm's law?

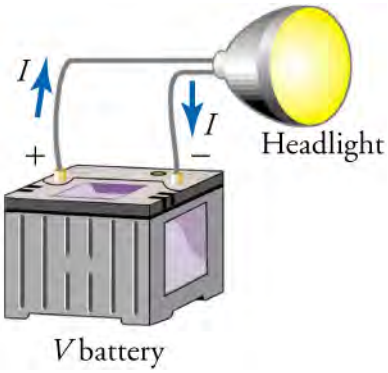
a. The current will get doubled. This conforms to Ohm's law as the current is proportional to the voltage.
b. The current will double. This does not conform to Ohm's law as the current is proportional to the voltage.

c. The current will increase by half. This conforms to Ohm's law as the current is proportional to the voltage.
d. The current will decrease by half. This does not conform to Ohm's law as the current is proportional to the voltage.

WORKED EXAMPLE

Resistance of a Headlight

What is the resistance of an automobile headlight through which 2.50 A flows when 12.0 V is applied to it?



STRATEGY

Ohm's law tells us $V_{\text{headlight}} = IR_{\text{headlight}}$. The voltage drop in going through the headlight is just the voltage rise supplied by the battery, $V_{\text{headlight}} = V_{\text{battery}}$. We can use this equation and rearrange Ohm's law to find the resistance $R_{\text{headlight}}$ of the headlight.

Solution

Solving Ohm's law for the resistance of the headlight gives

$$\begin{aligned} V_{\text{headlight}} &= IR_{\text{headlight}} \\ V_{\text{battery}} &= IR_{\text{headlight}} \\ R_{\text{headlight}} &= \frac{V_{\text{battery}}}{I} = \frac{12\ \text{V}}{2.5\ \text{A}} = 4.8\ \Omega. \end{aligned} \tag{19.6}$$

Discussion

This is a relatively small resistance. As we will see below, resistances in circuits are commonly measured in kW or MW.

WORKED EXAMPLE

Determine Resistance from Current-Voltage Graph

Suppose you apply several different voltages across a circuit and measure the current that runs through the circuit. A plot of your results is shown in Figure 19.7. What is the resistance of the circuit?

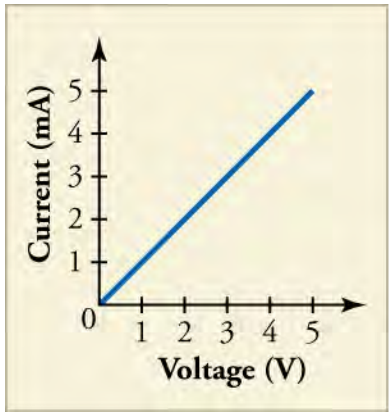


Figure 19.7 The line shows the current as a function of voltage. Notice that the current is given in milliamperes. For example, at 3 V, the current is 0.003 A, or 3 mA.

STRATEGY

The plot shows that current is proportional to voltage, which is Ohm's law. In Ohm's law ($V = IR$), the constant of proportionality is the resistance *R*. Because the graph shows current as a function of voltage, we have to rearrange Ohm's law in that form: $I = \frac{V}{R} = \frac{1}{R} \times V$. This shows that the slope of the line of *I* versus *V* is $\frac{1}{R}$. Thus, if we find the slope of the line in Figure 19.7, we can calculate the resistance *R*.

Solution

The slope of the line is the *rise* divided by the *run*. Looking at the lower-left square of the grid, we see that the line rises by 1 mA (0.001 A) and runs over a voltage of 1 V. Thus, the slope of the line is

$$\text{slope} = \frac{0.001\ \text{A}}{1\ \text{V}.} \tag{19.7}$$

Equating the slope with $\frac{1}{R}$ and solving for *R* gives

$$\begin{aligned} \frac{1}{R} &= \frac{0.001\ \text{A}}{1} \\ R &= \frac{1\ \text{V}}{0.001\ \text{A}} = 1{,}000\ \Omega \end{aligned} \tag{19.8}$$

or 1 k-ohm.

Discussion

This resistance is greater than what we found in the previous example. Resistances such as this are common in electric circuits, as we will discover in the next section. Note that if the line in Figure 19.7 were not straight, then the material would not be ohmic and we would not be able to use Ohm's law. Materials that do not follow Ohm's law are called **nonohmic**.

Practice Problems

3. If you double the voltage across an ohmic resistor, how does the current through the resistor change?
   a. The current will double.
   b. The current will increase by half.
   c. The current will decrease by half.
   d. The current will decrease by a factor of two.
4. The current through a $10\ \Omega$ resistor is 0.025 A. What is the voltage drop across the resistor?
   a. 2.5 mV
   b. 0.25 V
   c. 2.5 V
   d. 0.25 mV

Check Your Understanding

5. What is electric current?
   a. Electric current is the electric charge that is at rest.
   b. Electric current is the electric charge that is moving.
   c. Electric current is the electric charge that moves only from the positive terminal of a battery to the negative terminal.
   d. Electric current is the electric charge that moves only from a region of lower potential to higher potential.

6. What is an ohmic material?
   a. An ohmic material is a material that obeys Ohm's law.
   b. An ohmic material is a material that does not obey Ohm's law.
   c. An ohmic material is a material that has high resistance.
   d. An ohmic material is a material that has low resistance.

7. What is the difference between direct current and alternating current?
   a. Direct current flows continuously in every direction whereas alternating current flows in one direction.
   b. Direct current flows continuously in one direction whereas alternating current reverses its direction at regular time intervals.
   c. Both direct and alternating current flow in one direction but the magnitude of direct current is fixed whereas the magnitude of alternating current changes at regular intervals of time.
   d. Both direct and alternating current changes its direction of flow but the magnitude of direct current is fixed whereas the magnitude of alternating current changes at regular intervals of time.

19.2 Series Circuits

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Interpret circuit diagrams and diagram basic circuit elements
- Calculate equivalent resistance of resistors in series and apply Ohm's law to resistors in series and apply Ohm's law to resistors in series

Section Key Terms

circuit diagram	electric circuit	equivalent resistance
in series	resistor	steady state

Electric Circuits and Resistors

Now that we understand the concept of electric current, let's see what we can do with it. As you are no doubt aware, the modern lifestyle relies heavily on electrical devices. These devices contain ingenious **electric circuits**, which are complete, closed pathways through which electric current flows. Returning to our water analogy, an electric circuit is to electric charge like a network of pipes is to water: The electric circuit guides electric charge from one point to the next, running the charge through various devices along the way to extract work or information.

Electric circuits are made from many materials and cover a huge range of sizes, as shown in Figure 19.8. Computers and cell phones contain electric circuits whose features can be as small as roughly a billionth of a meter (a nanometer, or $10^{-9}\,\mathrm{m}$). The pathways that guide the current in these devices are made by ultraprecise chemical treatments of silicon or other semiconductors. Large power systems, on the other hand, contain electric circuits whose features are on the scale of meters. These systems carry such large electric currents that their physical dimensions must be relatively large.

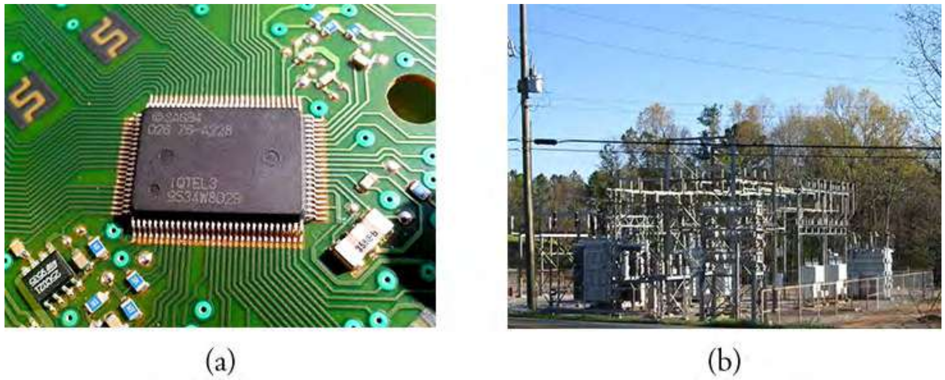


Figure 19.8 The photo on the left shows a *chip* that contains complex integrated electric circuitry. Chips such as this are at the heart of devices such as computers and cell phones. The photograph on the right shows some typical electric circuitry required for high-power electric power transmission.

The pathways that form electric circuits are made from a conducting material, normally a metal in macroscopic circuits. For example, copper wires inside your school building form the electrical circuits that power lighting, projectors, screens, speakers, etc. To represent an electric circuit, we draw **circuit diagrams**. We use lines and symbols to represent the elements in the circuit. A simple electric circuit diagram is shown on the left side of Figure 19.9. On the right side is an analogous water circuit, which we discuss below.

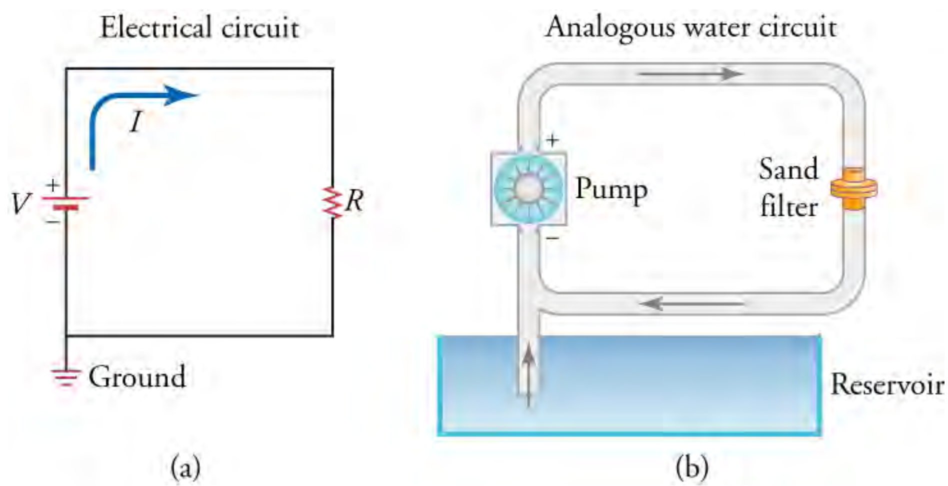


Figure 19.9 On the left is a circuit diagram showing a battery (in red), a resistor (black zigzag element), and the current *I*. On the right is the analogous water circuit. The pump is like the battery, the sand filter is like the resistor, the water current is like the electrical current, and the reservoir is like the ground.

There are many different symbols that scientists and engineers use in circuit diagrams, but we will focus on four main symbols: the wire, the battery or voltage source, resistors, and the ground. The thin black lines in the electric circuit diagram represent the pathway that the electric charge must follow. These pathways are assumed to be perfect conductors, so electric charge can move along these pathways without losing any energy. In reality, the wires in circuits are not perfect, but they come close enough for our purposes.

The zigzag element labeled *R* is a **resistor**, which is a circuit element that provides a known resistance. Macroscopic resistors are often color coded to indicate their resistance, as shown in Figure 19.10.

The red element in Figure 19.9 is a battery, with its positive and negative terminals indicated; the longer line represents the positive terminal of the battery, and the shorter line represents the negative terminal. Note that the battery icon is not always colored red; this is done in Figure 19.9 just to make it easy to identify.

Finally, the element labeled *ground* on the lower left of the circuit indicates that the circuit is connected to Earth, which is a large, essentially neutral object containing an infinite amount of charge. Among other things, the ground determines the potential of the negative terminal of the battery. Normally, the potential of the ground is defined to be zero: $V_{\text{ground}} \equiv 0$. This means that the entire lower wire in Figure 19.10 is at a voltage of zero volts.

Figure 19.10 Some typical resistors. The color bands indicate the value of the resistance of each resistor.

The electric current in Figure 19.9 is indicted by the blue line labeled *I*. The arrow indicates the direction in which positive charge would flow in this circuit. Recall that, in metals, electrons are mobile charge carriers, so negative charges actually flow in the opposite direction around this circuit (i.e., counterclockwise). However, we draw the current to show the direction in which positive charge would move.

On the right side of Figure 19.9 is an analogous water circuit. Water at a higher pressure leaves the top of the pump, which is like charges leaving the positive terminal of the battery. The water travels through the pipe, like the charges traveling through the wire. Next, the water goes through a sand filter, which heats up as the water squeezes through. This step is like the charges going through the resistor. When charges flow through a resistor, they do work to heat up the resistor. After flowing through the sand filter, the water has converted its potential energy into heat, so it is at a lower pressure. Likewise, the charges exiting the resistor have converted their potential energy into heat, so they are at a lower voltage. Recall that voltage is just potential energy per charge. Thus, water pressure is analogous to electric potential energy (i.e., voltage). Coming back to the water circuit again, we see that the water returns to the bottom of the pump, which is like the charge returning to the negative terminal of the battery. The water pump uses a source of energy to pump the water back up to a high pressure again, giving it the pressure required to go through the circuit once more. The water pump is like the battery, which uses chemical energy to increase the voltage of the charge up to the level of the positive terminal.

The potential energy per charge at the positive terminal of the battery is the voltage rating of the battery. This voltage is like water pressure in the upper pipe. Just like a higher pressure forces water to move toward a lower pressure, a higher voltage forces electric charge to flow toward a lower voltage. The pump takes water at low pressure and does work on it, ejecting water at a higher pressure. Likewise, a battery takes charge at a low voltage, does work on it, and ejects charge at a higher voltage.

Note that the current in the water circuit of Figure 19.9 is the same throughout the circuit. In other words, if we measured the number of water molecules passing a cross-section of the pipe per unit time at any point in the circuit, we would get the same answer no matter where in the circuit we measured. The same is true of the electrical circuit in the same figure. The electric current is the same at all points in this circuit, including inside the battery and in the resistor. The electric current neither speeds up in the wires nor slows down in the resistor. This would create points where too much or too little charge would be bunched up. Thus, the current is the same at all points in the circuit shown in Figure 19.9.

Although the current is the same everywhere in both the electric and water circuits, the voltage or water pressure changes as you move through the circuits. In the water circuit, the water pressure at the pump outlet stays the same until the water goes through the sand filter, assuming no energy loss in the pipe. Likewise, the voltage in the electrical circuit is the same at all points in a given wire, because we have assumed that the wires are perfect conductors. Thus, as indicated by the constant red color of the upper wire in Figure 19.11, the voltage throughout this wire is constant at $V = V_{\text{battery}}$. The voltage then drops as you go through the resistor, but once you reach the blue wire, the voltage stays at its new level of $V = 0$ all the way to the negative terminal of the battery (i.e., the blue terminal of the battery).

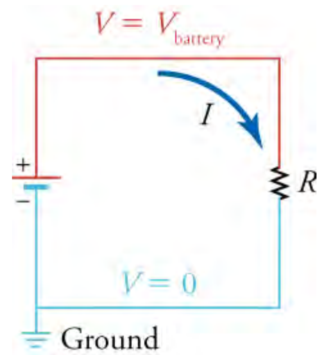


Figure 19.11 The voltage in the red wire is constant at $V = V_{\text{battery}}$ from the positive terminal of the battery to the top of the resistor. The voltage in the blue wire is constant at $V = V_{\text{ground}} = 0$ from the bottom of the resistor to the negative terminal of the battery.

If we go from the blue wire through the battery to the red wire, the voltage increases from $V = 0$ to $V = V_{\text{battery}}$. Likewise, if we go from the blue wire up through the resistor to the red wire, the voltage also goes from $V = 0$ to $V = V_{\text{battery}}$. Thus, using Ohm's law, we can write

$$V_{\text{resistor}} = V_{\text{battery}} = IR.$$

Note that V_{resistor} is measured from the bottom of the resistor to the top, meaning that the top of the resistor is at a higher voltage than the bottom of the resistor. Thus, current flows from the top of the resistor or higher voltage to the bottom of the resistor or lower voltage.

Virtual Physics

Battery-Resistor Circuit

Click to view content (http://www.openstax.org/l/21batteryresist)

Use this simulation to better understand how resistance, voltage, and current are related. The simulation shows a battery with a resistor connected between the terminals of the battery, as in the previous figure. You can modify the battery voltage and the resistance. The simulation shows how electrons react to these changes. It also shows the atomic cores in the resistor and how they are excited and heat up as more current goes through the resistor.

Draw the circuit diagram for the circuit, being sure to draw an arrow indicating the direction of the current. Now pick three spots along the wire. Without changing the settings, allow the simulation to run for 20 s while you count the number of electrons passing through that spot. Record the number on the circuit diagram. Now do the same thing at each of the other two spots in the circuit. What do you notice about the number of charges passing through each spot in 20 s? Remember that that current is defined as the rate that charges flow through the circuit. What does this mean about the current through the entire circuit?

GRASP CHECK

With the voltage slider, give the battery a positive voltage. Notice that the electrons are spaced farther apart in the left wire than they are in the right wire. How does this reflect the voltage in the two wires?

a. The voltage between static charges is directly proportional to the distance between them.
b. The voltage between static charges is directly proportional to square of the distance between them.
c. The voltage between static charges is inversely proportional to the distance between them.
d. The voltage between static charges is inversely proportional to square of the distance between them.

Other possible circuit elements include capacitors and switches. These are drawn as shown on the left side of Figure 19.12. A switch is a device that opens and closes the circuit, like a light switch. It is analogous to a valve in a water circuit, as shown on the right side of Figure 19.12. With the switch open, no current passes through the circuit. With the switch closed, it becomes part of the wire, so the current passes through it with no loss of voltage.

The capacitor is labeled C on the left of Figure 19.12. A capacitor in an electrical circuit is analogous to a flexible membrane in a water circuit. When the switch is closed in the circuit of Figure 19.12, the battery forces electrical current to flow toward the capacitor, charging the upper capacitor plate with positive charge. As this happens, the voltage across the capacitor plates increases. This is like the membrane in the water circuit: When the valve is opened, the pump forces water to flow toward the membrane, making it stretch to store the excess water. As this happens, the pressure behind the membrane increases.

Now if we open the switch, the capacitor holds the voltage between its plates because the charges have nowhere to go. Likewise, if we close the valve, the water has nowhere to go and the membrane maintains the water pressure in the pipe between itself and the valve.

If the switch is closed for a long time in the electric circuit or if the valve is open for a long time in the water circuit, the current will eventually stop flowing because the capacitor or the membrane will have become completely charged. Each circuit is now in the **steady state**, which means that its characteristics do not change over time. In this case, the steady state is characterized by zero current, and this does not change as long as the switch or valve remains in the same position. In the steady state, no electrical current passes through the capacitor, and no water current passes through the membrane. The voltage difference between the capacitor plates will be the same as the battery voltage. In the water circuit, the pressure behind the membrane will be the same as the pressure created by the pump.

Although the circuit in Figure 19.12 may seem a bit pointless because all that happens when the switch is closed is that the capacitor charges up, it does show the capacitor's ability to store charge. Thus, the capacitor serves as a reservoir for charge. This property of capacitors is used in circuits in many ways. For example, capacitors are used to power circuits while batteries are being charged. In addition, capacitors can serve as filters. To understand this, let's go back to the water analogy. Suppose you have a water hose and are watering your garden. Your friend thinks he's funny, and *kinks* the hose. While the hose is kinked, you experience no water flow. When he lets go, the water starts flowing again. If he does this really fast, you experience water-no water-water-no water, and that's really no way to water your garden. Now imagine that the hose is filling up a big bucket, and you are watering from the bottom of the bucket. As long as you had water in your bucket to begin with and your friend doesn't kink the water hose for too long, you would be able to water your garden without the interruptions. Your friend kinking the water hose is *filtered* by the big bucket's supply of water, so it does not impact your ability to water the garden. We can think of the interruptions in the current (be it water or electrical current) as *noise*. Capacitors act in an analogous way as the water bucket to help filter out the noise. Capacitors have so many uses that it is very rare to find an electronic circuit that does not include some capacitors.

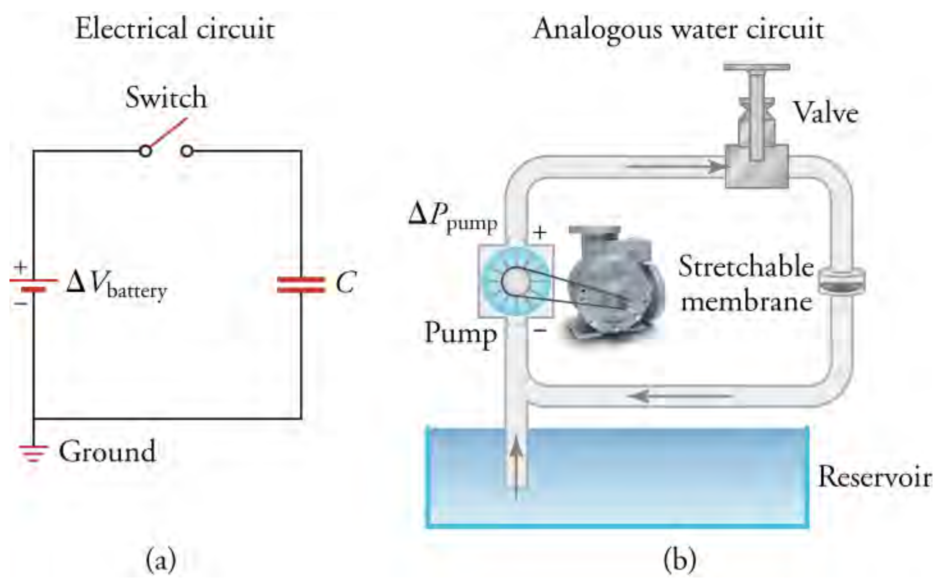


Figure 19.12 On the left is an electrical circuit containing a battery, a switch, and a capacitor. On the left is the analogous water circuit with a pump, a valve, and a stretchable membrane. The pump is like the battery, the valve is like the switch, and the stretchable membrane is like the capacitor. When the switch is closed, electrical current flows as the capacitor charges and its voltage increases. Likewise in the water circuit, when the valve is open, water current flows as the stretchable membrane stretches and the water pressure behind it increases.

WORK IN PHYSICS

What It Takes to be an Electrical Engineer

Physics is used in a wide variety of fields. One field that requires a very thorough knowledge of physics is electrical engineering. An electrical engineer can work on anything from the large-scale power systems that provide power to big cities to the nanoscale electronic circuits that are found in computers and cell phones (Figure 19.13).

In working with power companies, you can be responsible for maintaining the power grid that supplies electrical power to large areas. Although much of this work is done from an office, it is common to be called in for overtime duty after storms or other natural events. Many electrical engineers enjoy this part of the job, which requires them to race around the countryside repairing high-voltage transformers and other equipment. However, one of the more unpleasant aspects of this work is to remove the carcasses of unfortunate squirrels or other animals that have wandered into the transformers.

Other careers in electrical engineering can involve designing circuits for cell phones, which requires cramming some 10 billion transistors into an electronic chip the size of your thumbnail. These jobs can involve much work with computer simulations and can also involve fields other than electronics. For example, the 1-m-diameter lenses that are used to make these circuits (as of 2015) are so precise that they are shipped from the manufacture to the chip fabrication plant in temperature-controlled trucks to ensure that they are held within a certain temperature range. If they heat up or cool down too much, they deform ever so slightly, rendering them useless for the ultrahigh precision photolithography required to manufacture these chips.

In addition to a solid knowledge of physics, electrical engineers must above all be practical. Consider, for example, how one corporation managed to launch some anti-ballistic missiles at the White Sands Missile Test Range in New Mexico in the 1960s. Before launch, the skin of the missile had to be at the same voltage as the rail from which it was launched. The rail was connected to the ground by a large copper wire connected to a stake driven into the sandy earth. The missile, however, was connected by an umbilical cord to the equipment in the control shed a few meters away, which was grounded via a different grounding circuit. Before launching the missile, the voltage difference between the missile skin and the rail had to be less than 2.5 V. After an especially dry spell of weather, the missile could not be launched because the voltage difference stood at 5 V. A group of electrical engineers, including the father of your author, stood around pondering how to reduce the voltage difference. The situation was resolved when one of the engineers realized that urine contains electrolytes and conducts electricity quite well. With that, the four engineers quickly resolved the problem by urinating on the rail spike. The voltage difference immediately dropped to below 2.5 V and the missile was launched on schedule.

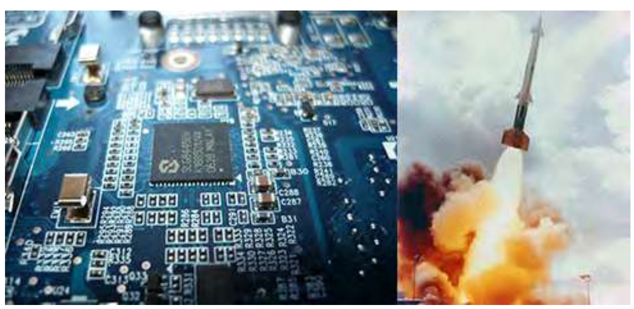


Figure 19.13 The systems that electrical engineers work on range from microprocessor circuits (left)] to missile systems (right).

Virtual Physics

Click to view content (http://www.openstax.org/l/21phetcirconstr)

Amuse yourself by building circuits of all different shapes and sizes. This simulation provides you with various standard circuit elements, such as batteries, AC voltage sources, resistors, capacitors, light bulbs, switches, etc. You can connect these in any configuration you like and then see the result.

Build a circuit that starts with a resistor connected to a capacitor. Connect the free side of the resistor to the positive terminal of a battery and the free side of the capacitor to the negative terminal of the battery. Click the *reset dynamics* button to see how the current flows starting with no charge on the capacitor. Now right click on the resistor to change its value. When you increase the resistance, does the circuit reach the steady state more rapidly or more slowly?

GRASP CHECK

When the circuit has reached the steady state, how does the voltage across the capacitor compare to the voltage of the battery? What is the voltage across the resistor?

a. The voltage across the capacitor is greater than the voltage of the battery. In the steady state, no current flows through this circuit, so the voltage across the resistor is zero.
b. The voltage across the capacitor is smaller than the voltage of the battery. In the steady state, finite current flows through this circuit, so the voltage across the resistor is finite.
c. The voltage across the capacitor is the same as the voltage of the battery. In the steady state, no current flows through this circuit, so the voltage across the resistor is zero.
d. The voltage across the capacitor is the same as the voltage of the battery. In the steady state, finite current flows through this circuit, so the voltage across the resistor is finite.

Resistors in Series and Equivalent Resistance

Now that we have a basic idea of how electrical circuits work, let's see what happens in circuits with more than one circuit element. In this section, we look at resistors in series. Components connected **in series** are connected one after the other in the same branch of a circuit, such as the resistors connected in series on the left side of Figure 19.14.

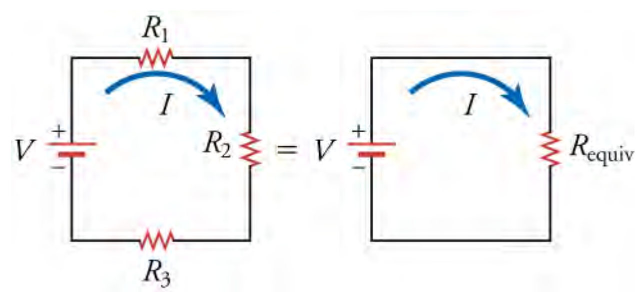


Figure 19.14 On the left is an electric circuit with three resistors R_1, R_2, and R_3 connected in series. On the right is an electric circuit with one resistor R_{equiv} that is equivalent to the combination of the three resistors R_1, R_2, and R_3.

We will now try to find a single resistance that is equivalent to the three resistors in series on the left side of Figure 19.14. An **equivalent resistor** is a resistor that has the same resistance as the combined resistance of a set of other resistors. In other words, the same current will flow through the left and right circuits in Figure 19.14 if we use the equivalent resistor in the right circuit.

According to Ohm's law, the voltage drop V across a resistor when a current flows through it is $V = IR$ where I is the current in amperes (A) and R is the resistance in ohms (Ω). Another way to think of this is that V is the voltage necessary to make a current I flow through a resistance R. Applying Ohm's law to each resistor on the left circuit of Figure 19.14, we find that the voltage drop across R_1 is $V_1 = IR_1$, that across R_2 is $V_2 = IR_2$, and that across R_3 is $V_3 = IR_3$. The sum of these voltages equals the voltage output of the battery, that is

$$V_{\text{battery}} = V_1 + V_2 + V_3. \quad (19.9)$$

You may wonder why voltages must add up like this. One way to understand this is to go once around the circuit and add up the successive changes in voltage. If you do this around a loop and get back to the starting point, the total change in voltage should be zero, because you end up at the same place that you started. To better understand this, consider the analogy of going for a stroll through some hilly countryside. If you leave your car and walk around, then come back to your car, the total height you gained in your stroll must be the same as the total height you lost, because you end up at the same place as you started. Thus, the gravitational potential energy you gain must be the same as the gravitational potential energy you lose. The same reasoning holds for voltage in going around an electric circuit. Let's apply this reasoning to the left circuit in Figure 19.14. We start just below the battery and move up through the battery, which contributes a voltage *gain* of V_{battery}. Next, we got through the resistors. The voltage *drops* by V_1 in going through resistor R_1, by V_2 in going through resistor R_2, and by V_3 in going through resistor R_3 . After going through resistor R_3, we arrive back at the starting point, so we add up these four changes in voltage and set the sum equal to zero. This gives

$$0 = V_{\text{battery}} - V_1 - V_2 - V_3. \tag{19.10}$$

which is the same as the previous equation. Note that the minus signs in front of V_1 ,V_2 , and V_3 are because these are voltage *drops*, whereas V_{battery} is a voltage *rise*.

Ohm's law tells us that $V_1 = IR_1$, $V_2 = IR_2$, and $V_3 = IR_3$. Inserting these values into equation $V_{\text{battery}} = V_1 + V_2 + V_3$ gives

$$\begin{aligned} V_{\text{battery}} &= IR_1 + IR_2 + IR_3 \\ &= I\left(R_1 + R_2 + R_3\right). \end{aligned} \tag{19.11}$$

Applying this same logic to the right circuit in Figure 19.14 gives

$$V_{\text{battery}} = IR_{\text{equiv}}. \tag{19.12}$$

Dividing the equation $V_{\text{battery}} = I\left(R_1 + R_2 + R_3\right)$ by $V_{\text{battery}} = IR_{\text{equiv}}$, we get

$$\begin{aligned} \frac{V_{\text{battery}}}{V_{\text{battery}}} &= \frac{I(R_1+R_2+R_3)}{IR_{\text{equiv}}} \\ R_{\text{equiv}} &= R_1 + R_2 + R_3. \end{aligned} \tag{19.13}$$

This shows that the equivalent resistance for a series of resistors is simply the sum of the resistances of each resistor. In general, N resistors connected in series can be replaced by an equivalent resistor with a resistance of

$$R_{\text{equiv}} = R_1 + R_2 + \cdots + R_N.$$

WATCH PHYSICS

Resistors in Series

This video discusses the basic concepts behind interpreting circuit diagrams and then shows how to calculate the equivalent resistance for resistors in series.

Click to view content (https://www.openstax.org/l/02resistseries)

GRASP CHECK

True or false—In a circuit diagram, we can assume that the voltage is the same at every point in a given wire.

a. false
b. true

WORKED EXAMPLE

Calculation of Equivalent Resistance

In the left circuit of the previous figure, suppose the voltage rating of the battery is 12 V, and the resistances are $R_1 = 1.0\ \Omega, R_2 = 6.0\ \Omega,\ \text{and} R_3 = 13\ \Omega$. (a) What is the equivalent resistance? (b) What is the current through the circuit?

STRATEGY FOR (A)

Use the equation for the equivalent resistance of resistors connected in series. Because the circuit has three resistances, we only need to keep three terms, so it takes the form

$$R_{\text{equiv}} = R_1 + R_2 + R_3. \tag{19.14}$$

Solution for (a)

Inserting the given resistances into the equation above gives

$$\begin{aligned} R_{\text{equiv}} &= R_1 + R_2 + R_3 \\ &= 1.0\ \Omega + 6.0\ \Omega + 13\ \Omega \\ &= 20\ \Omega. \end{aligned} \quad (19.15)$$

Discussion for (a)

We can thus replace the three resistors R_1, R_2, and R_3 with a single 20- Ω resistor.

STRATEGY FOR (B)

Apply Ohm's law to the circuit on the right side of the previous figure with the equivalent resistor of 20 Ω .

Solution for (b)

The voltage drop across the equivalent resistor must be the same as the voltage rise in the battery. Thus, Ohm's law gives

$$\begin{aligned} V_{\text{battery}} &= IR_{\text{equiv}} \\ I &= \frac{V_{\text{battery}}}{R_{\text{equiv}}} \\ &= \frac{12\ \text{V}}{20\ \Omega} \\ &= 0.60\ \text{A}. \end{aligned} \quad (19.16)$$

Discussion for (b)

To check that this result is reasonable, we calculate the voltage drop across each resistor and verify that they add up to the voltage rating of the battery. The voltage drop across each resistor is

$$\begin{aligned} V_1 &= IR_1 = (0.60\ \text{A})\,(1.0\Omega) = 0.60\ \text{V} \\ V_2 &= IR_2 = (0.60\ \text{A})\,(6.0\Omega) = 3.6\ \text{V} \\ V_3 &= IR_3 = (0.60\ \text{A})\,(13\Omega) = 7.8\ \text{V}. \end{aligned} \quad (19.17)$$

Adding these voltages together gives

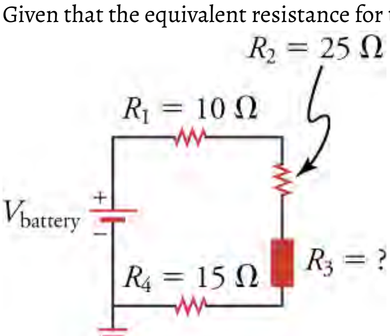
$$V_1 + V_2 + V_3 = 0.60\ \text{V} + 3.6\ \text{V} + 7.8\ \text{V} = 12\ \text{V}. \quad (19.18)$$

which is the voltage rating of the battery.

WORKED EXAMPLE

Determine the Unknown Resistance

The circuit shown in figure below contains three resistors of known value and a third element whose resistance R_3 is unknown. Given that the equivalent resistance for the entire circuit is 150 Ω, what is the resistance R_3 ?



STRATEGY

The four resistances in this circuit are connected in series, so we know that they must add up to give the equivalent resistance. We can use this to find the unknown resistance R_3 .

Solution

For four resistances in series, the equation for the equivalent resistance of resistors in series takes the form

$$R_{\text{equiv}} = R_1 + R_2 + R_3 + R_4. \quad (19.19)$$

Solving for R_3 and inserting the known values gives

$$\begin{aligned} R_3 &= R_{\text{equiv}} - R_1 - R_2 - R_4 \\ &= 150\ \Omega - 10\ \Omega - 25\ \Omega - 15\ \Omega \\ &= 100\ \Omega. \end{aligned} \tag{19.20}$$

Discussion

The equivalent resistance of a circuit can be measured with an ohmmeter. This is sometimes useful for determining the effective resistance of elements whose resistance is not marked on the element.

Check your Understanding

8.

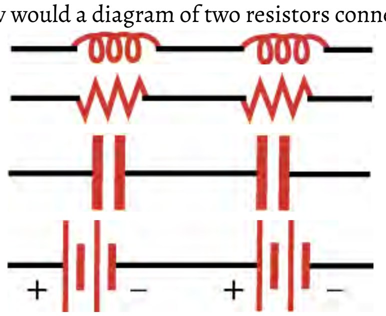
Figure 19.15

What circuit element is represented in the figure below?

a. a battery
b. a resistor
c. a capacitor
d. an inductor

9. How would a diagram of two resistors connected in series appear?

a.
b.
c.
d.



19.3 Parallel Circuits

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Interpret circuit diagrams with parallel resistors
- Calculate equivalent resistance of resistor combinations containing series and parallel resistors

Section Key Terms

in parallel

Resistors in Parallel

In the previous section, we learned that resistors in series are resistors that are connected one after the other. If we instead combine resistors by connecting them next to each other, as shown in Figure 19.16, then the resistors are said to be connected *in parallel*. Resistors are **in parallel** when both ends of each resistor are connected directly together.

Note that the tops of the resistors are all connected to the same wire, so the voltage at the top of the each resistor is the same. Likewise, the bottoms of the resistors are all connected to the same wire, so the voltage at the bottom of each resistor is the same. This means that the voltage drop across each resistor is the same. In this case, the voltage drop is the voltage rating V of the battery, because the top and bottom wires connect to the positive and negative terminals of the battery, respectively.

Although the voltage drop across each resistor is the same, we cannot say the same for the current running through each resistor. Thus, $I_1, I_2,$ and I_3 are not necessarily the same, because the resistors $R_1, R_2,$ and R_3 do not necessarily have the same resistance.

Note that the three resistors in Figure 19.16 provide three different paths through which the current can flow. This means that the equivalent resistance for these three resistors must be less than the smallest of the three resistors. To understand this, imagine that the smallest resistor is the only path through which the current can flow. Now add on the alternate paths by connecting other resistors in parallel. Because the current has more paths to go through, the overall resistance (i.e., the equivalent resistance) will decrease. Therefore, the equivalent resistance must be less than the smallest resistance of the parallel resistors.

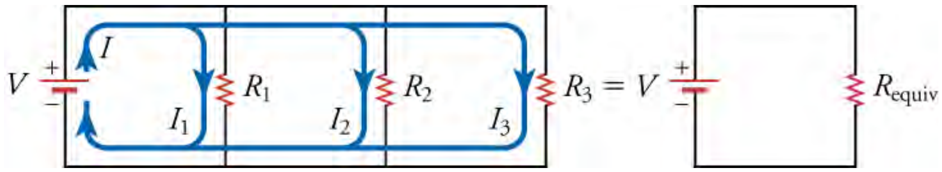


Figure 19.16 The left circuit diagram shows three resistors in parallel. The voltage *V* of the battery is applied across all three resistors. The currents that flow through each branch are not necessarily equal. The right circuit diagram shows an equivalent resistance that replaces the three parallel resistors.

To find the equivalent resistance R_{equiv} of the three resistors R_1, R_2, andR_3, we apply Ohm's law to each resistor. Because the voltage drop across each resistor is *V*, we obtain

$$V = I_1 R_1, \quad V = I_2 R_2, \quad V = I_3 R_3 \tag{19.21}$$

or

$$I_1 = \frac{V}{R_1}, \quad I_2 = \frac{V}{R_2}, \quad I_3 = \frac{V}{R_3.} \tag{19.22}$$

We also know from conservation of charge that the three currents I_1, I_2, andI_3 must add up to give the current *I* that goes through the battery. If this were not true, current would have to be mysteriously created or destroyed somewhere in the circuit, which is physically impossible. Thus, we have

$$I = I_1 + I_2 + I_3. \tag{19.23}$$

Inserting the expressions for I_1, I_2, andI_3 into this equation gives

$$I = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) \tag{19.24}$$

or

$$V = I\left(\frac{1}{1/R_1 + 1/R_2 + 1/R_3}\right). \tag{19.25}$$

This formula is just Ohm's law, with the factor in parentheses being the equivalent resistance.

$$V = I\left(\frac{1}{1/R_1 + 1/R_2 + 1/R_3}\right) = IR_{equiv.} \tag{19.26}$$

Thus, the equivalent resistance for three resistors in parallel is

$$R_{equiv} = \frac{1}{1/R_1 + 1/R_2 + 1/R_3}. \tag{19.27}$$

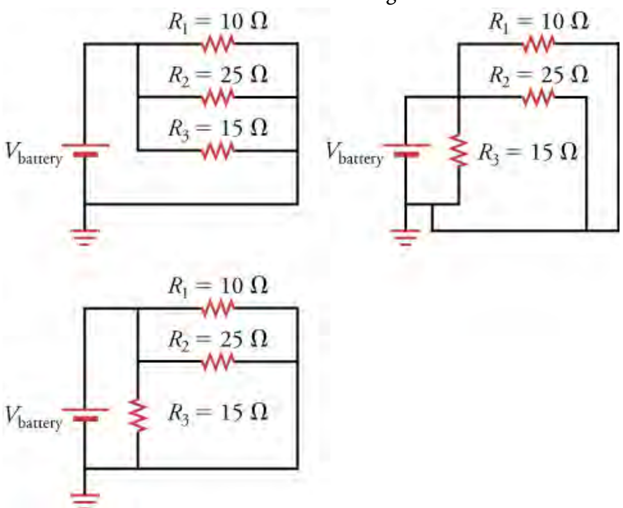
The same logic works for any number of resistors in parallel, so the general form of the equation that gives the equivalent resistance of *N* resistors connected in parallel is

$$R_{equiv} = \frac{1}{1/R_1 + 1/R_2 + \cdots + 1/R_N}. \tag{19.28}$$

WORKED EXAMPLE

Find the Current through Parallel Resistors

The three circuits below are equivalent. If the voltage rating of the battery is $V_{\text{battery}} = 3\text{ V}$, what is the equivalent resistance of the circuit and what current runs through the circuit?

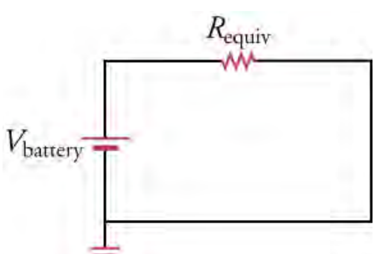


STRATEGY

The three resistors are connected in parallel and the voltage drop across them is V_{battery}. Thus, we can apply the equation for the equivalent resistance of resistors in parallel, which takes the form

$$R_{\text{equiv}} = \frac{1}{1/R_1 + 1/R_2 + 1/R_3}. \tag{19.29}$$

The circuit with the equivalent resistance is shown below. Once we know the equivalent resistance, we can use Ohm's law to find the current in the circuit.



Solution

Inserting the given values for the resistance into the equation for equivalent resistance gives

$$\begin{aligned} R_{\text{equiv}} &= \frac{1}{1/R_1+1/R_2+1/R_3} \\ &= \frac{1}{1/10\ \Omega+1/25\ \Omega+1/15\ \Omega} \\ &= 4.84\ \Omega. \end{aligned} \tag{19.30}$$

The current through the circuit is thus

$$\begin{aligned} V &= IR \\ I &= \frac{V}{R} \\ &= \frac{3\text{ V}}{4.84\ \Omega} \\ &= 0.62\text{ A}. \end{aligned} \tag{19.31}$$

Discussion

Although 0.62 A flows through the entire circuit, note that this current does not flow through each resistor. However, because electric charge must be conserved in a circuit, the sum of the currents going through each branch of the circuit must add up to the current going through the battery. In other words, we cannot magically create charge somewhere in the circuit and add this new charge to the current. Let's check this reasoning by using Ohm's law to find the current through each resistor.

$$\begin{aligned} I_1 &= \frac{V}{R_1} = \frac{3\ \text{V}}{10\ \Omega} = 0.30\ \text{A} \\ I_2 &= \frac{V}{R_2} = \frac{3\ \text{V}}{25\ \Omega} = 0.12\ \text{A} \\ I_3 &= \frac{V}{R_3} = \frac{3\ \text{V}}{15\ \Omega} = 0.20\ \text{A} \end{aligned} \tag{19.32}$$

As expected, these currents add up to give 0.62 A, which is the total current found going through the equivalent resistor. Also, note that the smallest resistor has the largest current flowing through it, and vice versa.

WORKED EXAMPLE

Reasoning with Parallel Resistors

Without doing any calculation, what is the equivalent resistance of three identical resistors R in parallel?

STRATEGY

Three identical resistors R in parallel make three identical paths through which the current can flow. Thus, it is three times easier for the current to flow through these resistors than to flow through a single one of them.

Solution

If it is three times easier to flow through three identical resistors R than to flow through a single one of them, the equivalent resistance must be three times less: $R/3$.

Discussion

Let's check our reasoning by calculating the equivalent resistance of three identical resistors R in parallel. The equation for the equivalent resistance of resistors in parallel gives

$$\begin{aligned} R_{\text{equiv}} &= \frac{1}{1/R + 1/R + 1/R} \\ &= \frac{1}{3/R} \\ &= \frac{R}{3}. \end{aligned} \tag{19.33}$$

Thus, our reasoning was correct. In general, when more paths are available through which the current can flow, the equivalent resistance decreases. For example, if we have identical resistors R in parallel, the equivalent resistance would be $R/10$.

Practice Problems

10. Three resistors, 10, 20, and 30 Ω, are connected in parallel. What is the equivalent resistance?

a. The equivalent resistance is 5.5 Ω
b. The equivalent resistance is 60 Ω
c. The equivalent resistance is 6 × 103 Ω
d. The equivalent resistance is 6 × 104 Ω

11. If a 5-V drop occurs across R_1, and R_1 is connected in parallel to R_2, what is the voltage drop across R_2?

a. Voltage drop across is 0 V.
b. Voltage drop across is 2.5 V.
c. Voltage drop across is 5 V.
d. Voltage drop across is 10 V.

Resistors in Parallel and in Series

More complex connections of resistors are sometimes just combinations of series and parallel. Combinations of series and parallel resistors can be reduced to a single equivalent resistance by using the technique illustrated in Figure 19.17. Various parts are identified as either series or parallel, reduced to their equivalents, and further reduced until a single resistance is left. The process is more time consuming than difficult.

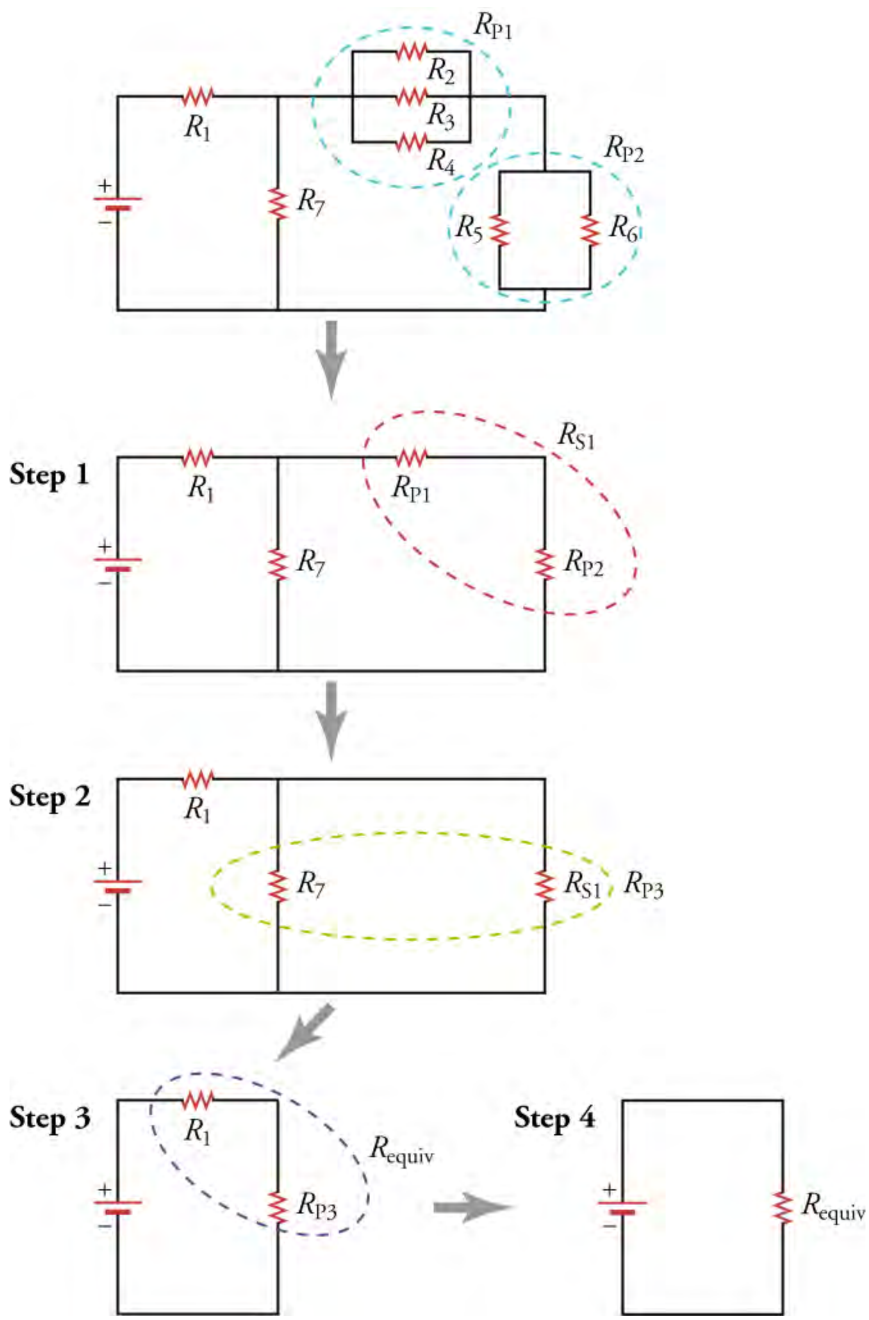


Figure 19.17 This combination of seven resistors has both series and parallel parts. Each is identified and reduced to an equivalent resistance, and these are further reduced until a single equivalent resistance is reached.

Let's work through the four steps in Figure 19.17 to reduce the seven resistors to a single equivalent resistor. To avoid distracting algebra, we'll assume each resistor is 10 Ω . In step 1, we reduce the two sets of parallel resistors circled by the blue dashed loop. The upper set has three resistors in parallel and will be reduced to a single equivalent resistor R_{P1} . The lower set has two resistors in parallel and will be reduced to a single equivalent resistor R_{P2} . Using the equation for the equivalent resistance of resistors in parallel, we obtain

$$\begin{aligned} R_{\text{P1}} &= \frac{1}{1/R_2+1/R_3+1/R_4} &= \frac{1}{1/10\ \Omega+1/10\ \Omega+1/10\ \Omega} &= \frac{10}{3}\Omega \\ R_{\text{P2}} &= \frac{1}{1/R_5+1/R_6} &= \frac{1}{1/10\ \Omega+1/10\ \Omega} &= 5\ \Omega. \end{aligned} \tag{19.34}$$

These two equivalent resistances are encircled by the red dashed loop following step 1. They are in series, so we can use the equation for the equivalent resistance of resistors in series to reduce them to a single equivalent resistance R_{S1}. This is done in step 2, with the result being

$$R_{S1} = R_{P1} + R_{P2} = \frac{10}{3}\Omega + 5\ \Omega = \frac{25}{3}\Omega. \tag{19.35}$$

The equivalent resistor R_{S1} appears in the green dashed loop following step 2. This resistor is in parallel with resistor R_7, so the pair can be replaced by the equivalent resistor R_{P3}, which is given by

$$R_{P3} = \frac{1}{1/R_{S1} + 1/R_7} = \frac{1}{3/25\ \Omega + 1/10\ \Omega} = \frac{50}{11}\Omega. \tag{19.36}$$

This is done in step 3. The resistor R_{P3} is in series with the resistor R_1, as shown in the purple dashed loop following step 3. These two resistors are combined in the final step to form the final equivalent resistor R_{equiv}, which is

$$R_{\text{equiv}} = R_1 + R_{P3} = 10\ \Omega + \frac{50}{11}\Omega = \frac{160}{11}\Omega. \tag{19.37}$$

Thus, the entire combination of seven resistors may be replaced by a single resistor with a resistance of about 14.5 Ω.

That was a lot of work, and you might be asking why we do it. It's important for us to know the equivalent resistance of the entire circuit so that we can calculate the current flowing through the circuit. Ohm's law tells us that the current flowing through a circuit depends on the resistance of the circuit and the voltage across the circuit. But to know the current, we must first know the equivalent resistance.

Here is a general approach to find the equivalent resistor for any arbitrary combination of resistors:

1. Identify a group of resistors that are only in parallel or only in series.
2. For resistors in series, use the equation for the equivalent resistance of resistors in series to reduce them to a single equivalent resistance. For resistors in parallel, use the equation for the equivalent resistance of resistors in parallel to reduce them to a single equivalent resistance.
3. Draw a new circuit diagram with the resistors from step 1 replaced by their equivalent resistor.
4. If more than one resistor remains in the circuit, return to step 1 and repeat. Otherwise, you are finished.

FUN IN PHYSICS

Robot

Robots have captured our collective imagination for over a century. Now, this dream of creating clever machines to do our dirty work, or sometimes just to keep us company, is becoming a reality. *Robotics* has become a huge field of research and development, with some technology already being commercialized. Think of the small autonomous vacuum cleaners, for example.

Figure 19.18 shows just a few of the multitude of different forms robots can take. The most advanced humanoid robots can walk, pour drinks, even dance (albeit not very gracefully). Other robots are bio-inspired, such as the *dogbot* shown in the middle photograph of Figure 19.18. This robot can carry hundreds of pounds of load over rough terrain. The photograph on the right in Figure 19.18 shows the inner workings of an *M-block*, developed by the Massachusetts Institute of Technology. These simple-looking blocks contain inertial wheels and electromagnets that allow them to spin and flip into the air and snap together in a variety of shapes. By communicating wirelessly between themselves, they self-assemble into a variety of shapes, such as desks, chairs, and someday maybe even buildings.

All robots involve an immense amount of physics and engineering. The simple act of pouring a drink has only recently been mastered by robots, after over 30 years of research and development! The balance and timing that we humans take for granted is in fact a very tricky act to follow, requiring excellent balance, dexterity, and feedback. To master this requires sensors to detect balance, computing power to analyze the data and communicate the appropriate compensating actions, and joints and actuators to implement the required actions.

In addition to sensing gravity or acceleration, robots can contain multiple different sensors to detect light, sound, temperature, smell, taste, etc. These devices are all based on the physical principles that you are studying in this text. For example, the optics used for robotic vision are similar to those used in your digital cameras: pixelated semiconducting detectors in which light is converted into electrical signals. To detect temperature, simple thermistors may be used, which are resistors whose resistance changes depending on temperature.

Building a robot today is much less arduous than it was a few years ago. Numerous companies now offer kits for building robots. These range in complexity something suitable for elementary school children to something that would challenge the best professional engineers. If interested, you may find these easily on the Internet and start making your own robot today.

Figure 19.18 Robots come in many shapes and sizes, from the classic *humanoid* type to *dogbots* to small cubes that self-assemble to perform a variety of tasks.

WATCH PHYSICS

Resistors in Parallel

This video shows a lecturer discussing a simple circuit with a battery and a pair of resistors in parallel. He emphasizes that electrons flow in the direction opposite to that of the positive current and also makes use of the fact that the voltage is the same at all points on an ideal wire. The derivation is quite similar to what is done in this text, but the lecturer goes through it well, explaining each step.

Click to view content (https://www.openstax.org/l/28resistors)

GRASP CHECK

True or false—In a circuit diagram, we can assume that the voltage is the same at every point in a given wire.

a. false
b. true

WATCH PHYSICS

Resistors in Series and in Parallel

This video shows how to calculate the equivalent resistance of a circuit containing resistors in parallel and in series. The lecturer uses the same approach as outlined above for finding the equivalent resistance.

Click to view content (https://www.openstax.org/l/28resistorssp)

GRASP CHECK

Imagine connected N identical resistors in parallel. Each resistor has a resistance of R. What is the equivalent resistance for this group of parallel resistors?

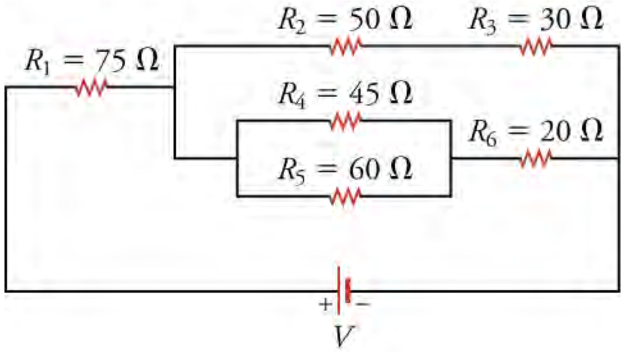
a. The equivalent resistance is $(R)^N$.

b. The equivalent resistance is NR.
c. The equivalent resistance is $\frac{R}{N}$.
d. The equivalent resistance is $\frac{N}{R}$.

WORKED EXAMPLE

Find the Current through a Complex Resistor Circuit

The battery in the circuit below has a voltage rating of 10 V. What current flows through the circuit and in what direction?



STRATEGY

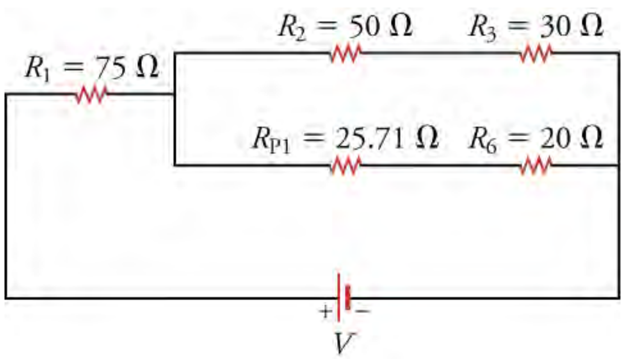
Apply the strategy for finding equivalent resistance to replace all the resistors with a single equivalent resistance, then use Ohm's law to find the current through the equivalent resistor.

Solution

The resistor combination R_4 and R_5 can be reduced to an equivalent resistance of

$$R_{\mathrm{P1}} = \frac{1}{1/R_4 + 1/R_5} = \frac{1}{1/45\ \Omega + 1/60\ \Omega} = 25.71\ \Omega\mathrm{R}. \tag{19.38}$$

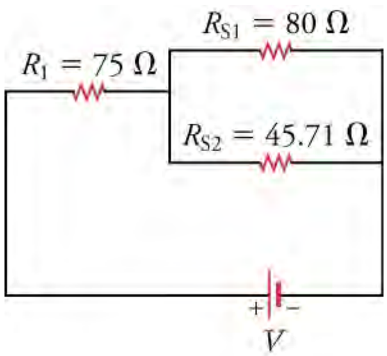
Replacing R_4 and R_5 with this equivalent resistance gives the circuit below.



We now replace the two upper resistors R_2 and R_3 by the equivalent resistor R_{S1} and the two lower resistors R_{P1} and R_6 by their equivalent resistor R_{S2} . These resistors are in series, so we add them together to find the equivalent resistance.

$$\begin{aligned} R_{\mathrm{S1}} &= R_2 + R_3 &&= 50\ \Omega + 30\ \Omega &&= 80\ \Omega \\ R_{\mathrm{S2}} &= R_{\mathrm{P1}} + R_6 &&= 25.71\ \Omega + 20\ \Omega &&= 45.71\ \Omega \end{aligned} \tag{19.39}$$

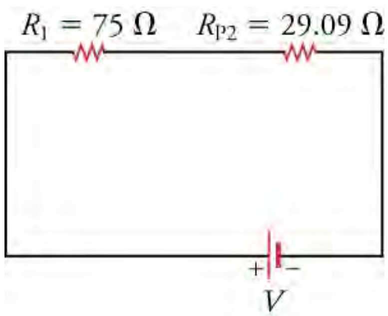
Replacing the relevant resistors with their equivalent resistor gives the circuit below.



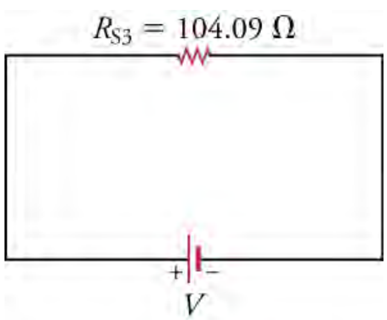
Now replace the two resistors R_{S1} and R_{S2}, which are in parallel, with their equivalent resistor R_{P2}. The resistance of R_{P2} is

$$R_{P2} = \frac{1}{1/R_{S1} + 1/R_{S2}} = \frac{1}{1/80\ \Omega + 1/45.71\ \Omega} = 29.09\ \Omega. \tag{19.40}$$

Updating the circuit diagram by replacing R_{S1} and R_{S2} with this equivalent resistance gives the circuit below.



Finally, we combine resistors R_1 and R_{P2}, which are in series. The equivalent resistance is $R_{S3} = R_1 + R_{P2} = 75\ \Omega + 29.09\ \Omega = 104.09\ \Omega$. The final circuit is shown below.



We now use Ohm's law to find the current through the circuit.

$$\begin{aligned} V &= IR_{S3} \\ I &= \frac{V}{R_{S3}} = \frac{10\ \text{V}}{104.09\ \Omega} = 0.096\ \text{A} \end{aligned} \tag{19.41}$$

The current goes from the positive terminal of the battery to the negative terminal of the battery, so it flows clockwise in this circuit.

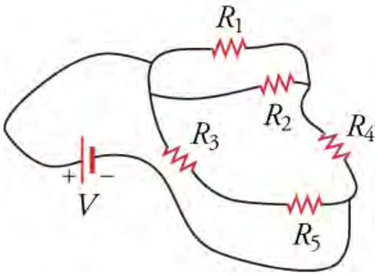
Discussion

This calculation may seem rather long, but with a little practice, you can combine some steps. Note also that extra significant digits were carried through the calculation. Only at the end was the final result rounded to two significant digits.

WORKED EXAMPLE

Strange-Looking Circuit Diagrams

Occasionally, you may encounter circuit diagrams that are not drawn very neatly, such as the diagram shown below. This circuit diagram looks more like how a real circuit might appear on the lab bench. What is the equivalent resistance for the resistors in this diagram, assuming each resistor is 10 Ω and the voltage rating of the battery is 12 V.

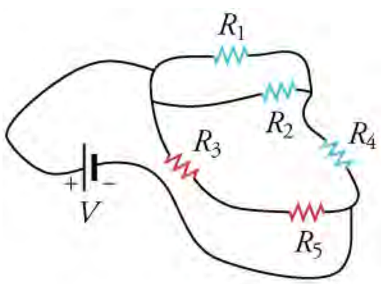


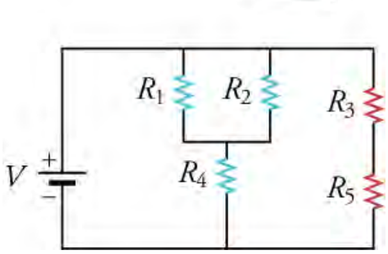
STRATEGY

Let's redraw this circuit diagram to make it clearer. Then we'll apply the strategy outlined above to calculate the equivalent resistance.

Solution

To redraw the diagram, consider the figure below. In the upper circuit, the blue resistors constitute a path from the positive terminal of the battery to the negative terminal. In parallel with this circuit are the red resistors, which constitute another path from the positive to negative terminal of the battery. The blue and red paths are shown more cleanly drawn in the lower circuit diagram. Note that, in both the upper and lower circuit diagrams, the blue and red paths connect the positive terminal of the battery to the negative terminal of the battery.





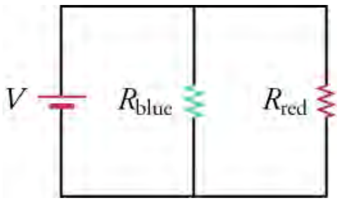
Now it is easier to see that R_1 and R_2 are in parallel, and the parallel combination is in series with R_4 . This combination in turn is in parallel with the series combination of R_3 and R_5 . First, we calculate the blue branch, which contains R_1 , R_2, and R_4 . The equivalent resistance is

$$R_{\text{blue}} = \frac{1}{1/R_1 + 1/R_2} + R_4 = \frac{1}{1/10\Omega + 1/10\ \Omega} + 10\ \Omega = 15\ \Omega. \tag{19.42}$$

where we show the contribution from the parallel combination of resistors and from the series combination of resistors. We now calculate the equivalent resistance of the red branch, which is

$$R_{\text{red}} = R_3 + R_5 = 10\ \Omega + 10\ \Omega = 20\ \Omega. \tag{19.43}$$

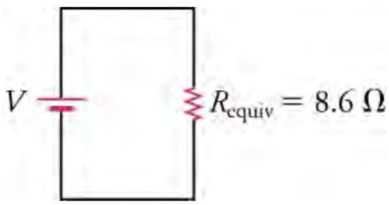
Inserting these equivalent resistors into the circuit gives the circuit below.



These two resistors are in parallel, so they can be replaced by a single equivalent resistor with a resistance of

$$R_{\text{equiv}} = \frac{1}{1/R_{\text{blue}} + 1/R_{\text{red}}} = \frac{1}{1/15\ \Omega + 1/20\ \Omega} = 8.6\ \Omega. \tag{19.44}$$

The final equivalent circuit is show below.



Discussion

Finding the equivalent resistance was easier with a clear circuit diagram. This is why we try to make clear circuit diagrams, where the resistors in parallel are lined up parallel to each other and at the same horizontal position on the diagram.

We can now use Ohm's law to find the current going through each branch to this circuit. Consider the circuit diagram with R_{blue} and R_{red} . The voltage across each of these branches is 12 V (i.e., the voltage rating of the battery). The current in the blue branch is

$$I_{\text{blue}} = \frac{V}{R_{\text{blue}}} = \frac{12\ \text{V}}{15\ \Omega} = 0.80\ \text{A}. \tag{19.45}$$

The current across the red branch is

$$I_{\text{red}} = \frac{V}{R_{\text{red}}} = \frac{12\ \text{V}}{20\ \Omega} = 0.60\ \text{A}. \tag{19.46}$$

The current going through the battery must be the sum of these two currents (can you see why?), or 1.4 A.

Practice Problems

12. What is the formula for the equivalent resistance of two parallel resistors with resistance R_1 and R_2?

a. Equivalent resistance of two parallel resistors $R_{\text{eqv}} = R_1 + R_2$
b. Equivalent resistance of two parallel resistors $R_{\text{eqv}} = R_1 \times R_2$
c. Equivalent resistance of two parallel resistors $R_{\text{eqv}} = R_1 - R_2$
d. Equivalent resistance of two parallel resistors $R_{\text{eqv}} = \frac{1}{1/R_1 + 1/R_2}$

13.

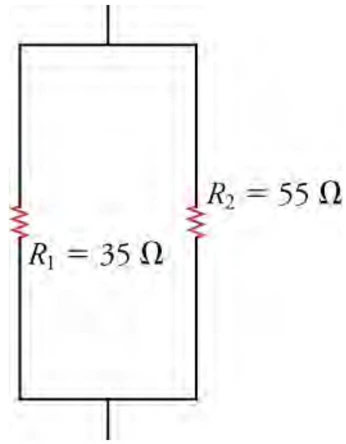


Figure 19.19

What is the equivalent resistance for the two resistors shown below?

a. The equivalent resistance is 20 Ω
b. The equivalent resistance is 21 Ω
c. The equivalent resistance is 90 Ω
d. The equivalent resistance is 1,925 Ω

Check Your Understanding

14. The voltage drop across parallel resistors is ________.

a. the same for all resistors
b. greater for the larger resistors
c. less for the larger resistors
d. greater for the smaller resistors

15. Consider a circuit of parallel resistors. The smallest resistor is 25 Ω . What is the upper limit of the equivalent resistance?

a. The upper limit of the equivalent resistance is 2.5 Ω.
b. The upper limit of the equivalent resistance is 25 Ω.
c. The upper limit of the equivalent resistance is 100 Ω.
d. There is no upper limit.

19.4 Electric Power

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Define electric power and describe the electric power equation
- Calculate electric power in circuits of resistors in series, parallel, and complex arrangements

Section Key Terms

electric power

Power is associated by many people with electricity. Every day, we use electric power to run our modern appliances. Electric power transmission lines are visible examples of electricity providing power. We also use electric power to start our cars, to run our computers, or to light our homes. Power is the rate at which energy of any type is transferred; **electric power** is the rate at which electric energy is transferred in a circuit. In this section, we'll learn not only what this means, but also what factors determine electric power.

To get started, let's think of light bulbs, which are often characterized in terms of their power ratings in watts. Let us compare a 25-W bulb with a 60-W bulb (see Figure 19.20). Although both operate at the same voltage, the 60-W bulb emits more light intensity than the 25-W bulb. This tells us that something other than voltage determines the power output of an electric circuit.

Incandescent light bulbs, such as the two shown in Figure 19.20, are essentially resistors that heat up when current flows through them and they get so hot that they emit visible and invisible light. Thus the two light bulbs in the photo can be considered as two different resistors. In a simple circuit such as a light bulb with a voltage applied to it, the resistance determines the current by Ohm's law, so we can see that current as well as voltage must determine the power.

Figure 19.20 On the left is a 25-W light bulb, and on the right is a 60-W light bulb. Why are their power outputs different despite their operating on the same voltage?

The formula for power may be found by dimensional analysis. Consider the units of power. In the SI system, power is given in watts (W), which is energy per unit time, or J/s

$$\mathrm{W} = \frac{\mathrm{J}}{\mathrm{s}}. \quad (19.47)$$

Recall now that a voltage is the potential energy per unit charge, which means that voltage has units of J/C

$$\mathrm{V} = \frac{\mathrm{J}}{\mathrm{C}}. \quad (19.48)$$

We can rewrite this equation as $\mathrm{J} = \mathrm{V} \times \mathrm{C}$ and substitute this into the equation for watts to get

$$\mathrm{W} = \frac{\mathrm{J}}{\mathrm{s}} = \frac{\mathrm{V} \times \mathrm{C}}{\mathrm{s}} = \mathrm{V} \times \frac{\mathrm{C}}{\mathrm{s}}.$$

But a Coulomb per second (C/s) is an electric current, which we can see from the definition of electric current, $I = \frac{\Delta Q}{\Delta t}$, where ΔQ is the charge in coulombs and Δt is time in seconds. Thus, equation above tells us that electric power is voltage times current, or

$$P = IV.$$

This equation gives the electric power consumed by a circuit with a voltage drop of V and a current of I.

For example, consider the circuit in Figure 19.21. From Ohm's law, the current running through the circuit is

$$I = \frac{V}{R} = \frac{12\ \mathrm{V}}{100\ \Omega} = 0.12\ \mathrm{A}. \quad (19.49)$$

Thus, the power consumed by the circuit is

$$P = VI = (12\ \mathrm{V})(0.12\ \mathrm{A}) = 1.4\ \mathrm{W}. \quad (19.50)$$

Where does this power go? In this circuit, the power goes primarily into heating the resistor in this circuit.

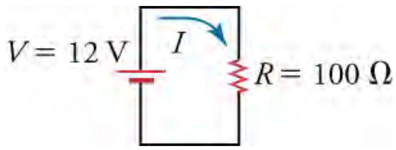


Figure 19.21 A simple circuit that consumes electric power.

In calculating the power in the circuit of Figure 19.21, we used the resistance and Ohm's law to find the current. Ohm's law gives the current: $I = V/R$, which we can insert into the equation for electric power to obtain

$$P = IV = \left(\frac{V}{R}\right)V = \frac{V^2}{R}.$$

This gives the power in terms of only the voltage and the resistance.

We can also use Ohm's law to eliminate the voltage in the equation for electric power and obtain an expression for power in terms of just the current and the resistance. If we write Ohm's law as $V = IR$ and use this to eliminate V in the equation $P = IV$, we obtain

$$P = IV = I\,(IR) = I^2 R.$$

This gives the power in terms of only the current and the resistance.

Thus, by combining Ohm's law with the equation $P = IV$ for electric power, we obtain two more expressions for power: one in terms of voltage and resistance and one in terms of current and resistance. Note that only resistance (not capacitance or anything else), current, and voltage enter into the expressions for electric power. This means that the physical characteristic of a circuit that determines how much power it dissipates is its resistance. Any capacitors in the circuit do not dissipate electric power—on the contrary, capacitors either store electric energy or release electric energy back to the circuit.

To clarify how voltage, resistance, current, and power are all related, consider Figure 19.22, which shows the *formula wheel*. The quantities in the center quarter circle are equal to the quantities in the corresponding outer quarter circle. For example, to express a potential V in terms of power and current, we see from the formula wheel that $V = P/I$.

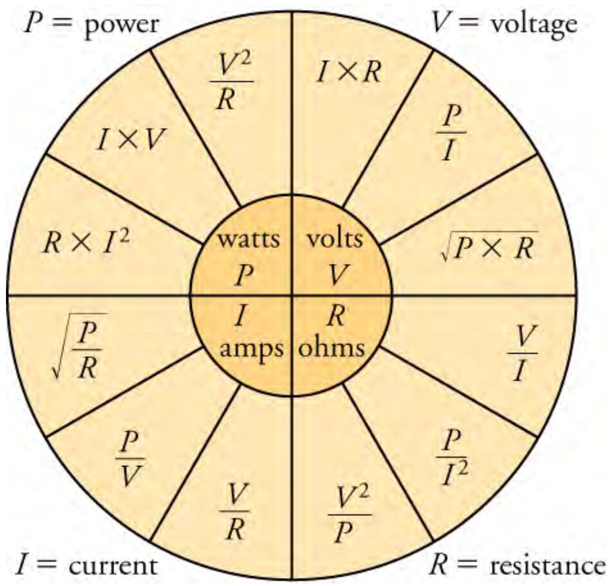


Figure 19.22 The formula wheel shows how volts, resistance, current, and power are related. The quantities in the inner quarter circles equal the quantities in the corresponding outer quarter circles.

WORKED EXAMPLE

Find the Resistance of a Lightbulb

A typical older incandescent lightbulb was 60 W. Assuming that 120 V is applied across the lightbulb, what is the current through the lightbulb?

STRATEGY

We are given the voltage and the power output of a simple circuit containing a lightbulb, so we can use the equation $P = IV$ to find the current I that flows through the lightbulb.

Solution

Solving $P = IV$ for the current and inserting the given values for voltage and power gives

$$\begin{aligned} P &= IV \\ I &= \frac{P}{V} = \frac{60\ \text{W}}{120\ \text{V}} = 0.50\ \text{A}. \end{aligned} \quad (19.51)$$

Thus, a half ampere flows through the lightbulb when 120 V is applied across it.

Discussion

This is a significant current. Recall that household power is AC and not DC, so the 120 V supplied by household sockets is an alternating power, not a constant power. The 120 V is actually the time-averaged power provided by such sockets. Thus, the average current going through the light bulb over a period of time longer than a few seconds is 0.50 A.

WORKED EXAMPLE

Boot Warmers

To warm your boots on cold days, you decide to sew a circuit with some resistors into the insole of your boots. You want 10 W of heat output from the resistors in each insole, and you want to run them from two 9-V batteries (connected in series). What total resistance should you put in each insole?

STRATEGY

We know the desired power and the voltage (18 V, because we have two 9-V batteries connected in series), so we can use the equation $P = V^2/R$ to find the requisite resistance.

Solution

Solving $P = V^2/R$ for the resistance and inserting the given voltage and power, we obtain

$$\begin{aligned} P &= \frac{V^2}{R} \\ R &= \frac{V^2}{P} = \frac{(18\ \text{V})^2}{10\ \text{W}} = 32\ \Omega. \end{aligned} \tag{19.52}$$

Thus, the total resistance in each insole should be 32 Ω.

Discussion

Let's see how much current would run through this circuit. We have 18 V applied across a resistance of 32 Ω, so Ohm's law gives

$$I = \frac{V}{R} = \frac{18\ \text{V}}{32\ \Omega} = 0.56\ \text{A}. \tag{19.53}$$

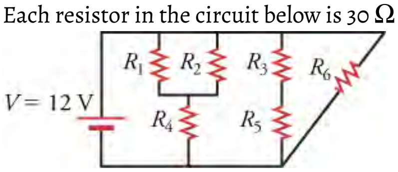
All batteries have labels that say how much charge they can deliver (in terms of a current multiplied by a time). A typical 9-V alkaline battery can deliver a charge of 565 $\text{mA} \cdot \text{h}$ (so two 9 V batteries deliver 1,130 $\text{mA} \cdot \text{h}$), so this heating system would function for a time of

$$t = \frac{1130\ \times\ 10^{-3}\text{A} \cdot \text{h}}{0.56\ \text{A}} = 2.0\ \text{h}. \tag{19.54}$$

WORKED EXAMPLE

Power through a Branch of a Circuit

Each resistor in the circuit below is 30 Ω . What power is dissipated by the middle branch of the circuit?



STRATEGY

The middle branch of the circuit contains resistors R_3 and R_5 in series. The voltage across this branch is 12 V. We will first find the equivalent resistance in this branch, and then use $P = V^2/R$ to find the power dissipated in the branch.

Solution

The equivalent resistance is $R_{\text{middle}} = R_3 + R_5 = 30\ \Omega + 30\ \Omega = 60\ \Omega$. The power dissipated by the middle branch of the circuit is

$$P_{\text{middle}} = \frac{V^2}{R_{\text{middle}}} = \frac{(12\ \text{V})^2}{60\ \Omega} = 2.4\ \text{W}. \tag{19.55}$$

Discussion

Let's see if energy is conserved in this circuit by comparing the power dissipated in the circuit to the power supplied by the battery. First, the equivalent resistance of the left branch is

$$R_{\text{left}} = \frac{1}{1/R_1 + 1/R_2} + R_4 = \frac{1}{1/30\ \Omega + 1/30\ \Omega} + 30\ \Omega = 45\ \Omega. \tag{19.56}$$

The power through the left branch is

$$P_{\text{left}} = \frac{V^2}{R_{\text{left}}} = \frac{(12\ \text{V})^2}{45\ \Omega} = 3.2\ \text{W}. \tag{19.57}$$

The right branch contains only R_6, so the equivalent resistance is $R_{\text{right}} = R_6 = 30\ \Omega$. The power through the right branch is

$$P_{\text{right}} = \frac{V^2}{R_{\text{right}}} = \frac{(12\ \text{V})^2}{30\ \Omega} = 4.8\ \text{W}. \tag{19.58}$$

The total power dissipated by the circuit is the sum of the powers dissipated in each branch.

$$P = P_{\text{left}} + P_{\text{middle}} + P_{\text{right}} = 2.4\ \text{W} + 3.2\ \text{W} + 4.8\ \text{W} = 10.4\ \text{W} \tag{19.59}$$

The power provided by the battery is

$$P = IV. \tag{19.60}$$

where I is the total current flowing through the battery. We must therefore add up the currents going through each branch to obtain I. The branches contributes currents of

$$\begin{aligned} I_{\text{left}} &= \frac{V}{R_{\text{left}}} = \frac{12\ \text{V}}{45\ \Omega} = 0.2667\ \text{A} \\ \text{I}_{\text{middle}} &= \frac{V}{R_{\text{middle}}} = \frac{12\ \text{V}}{60\ \Omega} = 0.20\ \text{A} \\ \text{I}_{\text{right}} &= \frac{V}{R_{\text{right}}} = \frac{12\ \text{V}}{30\ \Omega} = 0.40\ \text{A}. \end{aligned} \tag{19.61}$$

The total current is

$$I = I_{\text{left}} + I_{\text{middle}} + I_{\text{right}} = 0.2667\ \text{A} + 0.20\ \text{A} + 0.40\ \text{A} = 0.87\ \text{A}. \tag{19.62}$$

and the power provided by the battery is

$$P = IV = (0.87\ \text{A})(12\ \text{V}) = 10.4\ \text{W}. \tag{19.63}$$

This is the same power as is dissipated in the resistors of the circuit, which shows that energy is conserved in this circuit.

Practice Problems

16. What is the formula for the power dissipated in a resistor?

a. The formula for the power dissipated in a resistor is $P = \frac{I}{V}$.
b. The formula for the power dissipated in a resistor is $P = \frac{V}{I}$.
c. The formula for the power dissipated in a resistor is $P = IV$.
d. The formula for the power dissipated in a resistor is $P = I^2V$.

17. What is the formula for power dissipated by a resistor given its resistance and the voltage across it?

a. The formula for the power dissipated in a resistor is $P = \frac{R}{V^2}$
b. The formula for the power dissipated in a resistor is $P = V^2R$
c. The formula for the power dissipated in a resistor is $P = \frac{V^2}{R}$
d. The formula for the power dissipated in a resistor is $P = I^2R$

Check your Understanding

18. Which circuit elements dissipate power?

a. capacitors
b. inductors
c. ideal switches
d. resistors

19. Explain in words the equation for power dissipated by a given resistance.

a. Electric power is proportional to current through the resistor multiplied by the square of the voltage across the resistor.
b. Electric power is proportional to square of current through the resistor multiplied by the voltage across the resistor.
c. Electric power is proportional to current through the resistor divided by the voltage across the resistor.
d. Electric power is proportional to current through the resistor multiplied by the voltage across the resistor.

KEY TERMS

alternating current electric current whose direction alternates back and forth at regular intervals
ampere unit for electric current; one ampere is one coulomb per second ($1\ \text{A} = 1\ \text{C/s}$)
circuit diagram schematic drawing of an electrical circuit including all circuit elements, such as resistors, capacitors, batteries, and so on
conventional current flows in the direction that a positive charge would flow if it could move
direct current electric current that flows in a single direction
electric circuit physical network of paths through which electric current can flow
electric current electric charge that is moving
electric power rate at which electric energy is transferred in a circuit
equivalent resistor resistance of a single resistor that is the same as the combined resistance of a group of resistors
in parallel when a group of resistors are connected side by side, with the top ends of the resistors connected together by a wire and the bottom ends connected together by a different wire
in series when elements in a circuit are connected one after the other in the same branch of the circuit
nonohmic material that does not follow Ohm's law
Ohm's law electric current is proportional to the voltage applied across a circuit or other path
ohmic material that obeys Ohm's law
resistance how much a circuit element opposes the passage of electric current; it appears as the constant of proportionality in Ohm's law
resistor circuit element that provides a known resistance
steady state when the characteristics of a system do not change over time

SECTION SUMMARY

19.1 Ohm's law

- Direct current is constant over time; alternating current alternates smoothly back and forth over time.
- Electrical resistance causes materials to extract work from the current that flows through them.
- In ohmic materials, voltage drop along a path is proportional to the current that runs through the path.

19.2 Series Circuits

- Circuit diagrams are schematic representations of electric circuits.
- Resistors in series are resistors that are connected head to tail.
- The same current runs through all resistors in series; however, the voltage drop across each resistor can be different.
- The voltage is the same at every point in a given wire.

19.3 Parallel Circuits

- The equivalent resistance of a group of N identical resistors R connected in parallel is R/N.
- Connecting resistors in parallel provides more paths for the current to go through, so the equivalent resistance is always less than the smallest resistance of the parallel resistors.
- The same voltage drop occurs across all resistors in parallel; however, the current through each resistor can differ.

19.4 Electric Power

- Electric power is dissipated in the resistances of a circuit. Capacitors do not dissipate electric power.
- Electric power is proportional to the voltage and the current in a circuit.
- Ohm's law provides two extra expressions for electric power: one that does not involve current and one that does not involve voltage.

KEY EQUATIONS

19.1 Ohm's law

electric current I is the charge ΔQ that passes a plane per unit time Δt	$I = \frac{\Delta Q}{\Delta t}$
an ampere is the coulombs per unit time that pass a plane	$1\ \text{A} = 1\ \text{C/s}$
Ohm's law: the current I is proportional to the voltage V, with the resistance R being the constant of proportionality	$V = IR$

19.2 Series Circuits

the equivalent resistance of N resistors connected in series	$R_{\text{equiv}} = R_1 + R_2 + \cdots + R_N$

19.3 Parallel Circuits

the equivalent resistance of N resistors connected in parallel	$R_{\text{equiv}} = \frac{1}{1/R_1 + 1/R_2 + \cdots + 1/R_N}$

19.4 Electric Power

for a given current I flowing through a potential difference V, the electric power dissipated	$P = IV$
for a given current I flowing through a resistance R, the electric power dissipated	$P = I^2R$
for a given voltage difference V across a resistor R, the electric power dissipated	$P = \frac{V^2}{R}$

CHAPTER REVIEW

Concept Items

19.1 Ohm's law

1. You connect a resistor across a battery. In which direction do the electrons flow?
   a. The electrons flow from the negative terminal of the battery to the positive terminal of the battery.
   b. The electrons flow from the positive terminal of the battery to the negative terminal of the battery.

2. How does current depend on resistance in Ohm's law?
   a. Current is directly proportional to the resistance.
   b. Current is inversely proportional to the resistance.
   c. Current is proportional to the square of the resistance.
   d. Current is inversely proportional to the square of the resistance.

3. In the context of electricity, what is resistance?
   a. Resistance is the property of materials to resist the passage of voltage.
   b. Resistance is the property of materials to resist the passage of electric current.
   c. Resistance is the property of materials to increase the passage of voltage.
   d. Resistance is the property of materials to increase the passage of electric current.

4. What is the mathematical formula for Ohm's law?
   a. $V = I^2R$
   b. $V = \frac{R}{I}$
   c. $V = \frac{I}{R}$
   d. $V = IR$

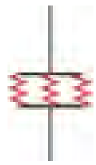
19.2 Series Circuits

5. In which circuit are all the resistors connected in series?

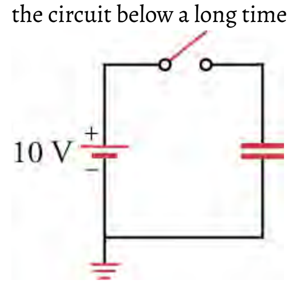
a. 

b. 

c. 

d. 

6. What is the voltage and current through the capacitor in the circuit below a long time after the switch is closed?



   a. 0 V, 0 A
   b. 0 V, 10 A
   c. 10 V, 0 A
   d. 10 V, 10 A

19.3 Parallel Circuits

7. If you remove resistance from a circuit, does the total resistance of the circuit always decrease? Explain.
   a. No, because for parallel combination of resistors, the resistance through the remaining circuit increases.
   b. Yes, because for parallel combination of resistors, the resistance through the remaining circuit increases.

8. Explain why the equivalent resistance of a parallel combination of resistors is always less than the smallest of the parallel resistors.
   a. Adding resistors in parallel gives the current a shorter path through which it can flow hence decreases the overall resistance.
   b. Adding resistors in parallel gives the current another path through which it can flow hence decreases the overall resistance.
   c. Adding resistors in parallel reduce the number of paths through which the current can flow hence decreases the overall resistance.
   d. Adding resistors in parallel gives the current longer path through which it can flow hence decreases the overall resistance.

19.4 Electric Power

9. To draw the most power from a battery, should you connect a small or a large resistance across its terminals? Explain.
   a. Small resistance, because smaller resistance will lead to the largest power
   b. Large resistance, because smaller resistance will lead to the largest power

10. If you double the current through a resistor, by what factor does the power dissipated by the resistor change?
   a. Power increases by a factor of two.
   b. Power increases by a factor of four.
   c. Power increases by a factor of eight.
   d. Power increases by a factor of 16.

Critical Thinking Items

19.1 Ohm's law

11. An accelerator accelerates He nuclei (change = $2e$) to a speed of $v = 2 \times 10^6$ m/s. What is the current if the linear density of He nuclei is $\lambda = 108\ \text{m}^{-1}$?
   a. $I = 9.6 \times 10^{-5}$ A
   b. $I = 3.2 \times 10^{-5}$ A
   c. $I = 12.8 \times 10^{-5}$ A
   d. $I = 6.4 \times 10^{-5}$ A

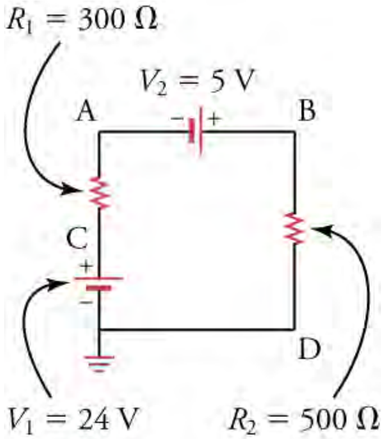
12. How can you verify whether a certain material is ohmic?
   a. Make a resistor from this material and measure the current going through this resistor for several different voltages. If the current is proportional to the voltage, then the material is ohmic.
   b. Make a resistor from this material and measure the current going through this resistor for several different voltages. If the current is inversely proportional to the voltage, then the material is ohmic.
   c. Make a resistor from this material and measure the current going through this resistor for several different voltages. If the current is proportional to the square of the voltage, then the material is ohmic.
   d. Make a resistor from this material and measure the current going through this resistor for several different voltages. If the current is inversely proportional to the square of the voltage, then the material is ohmic.

19.2 Series Circuits

13. Given three batteries (5V, 9V, 12V) and five resistors (10, 20, 30, 40, 50Ω) to choose from, what can you choose to form a circuit diagram with a current of 0.175A? You do not need to use all of the components.
   a. Batteries (5V, 9V) and resistors (30Ω, 50Ω) connected in series
   b. Batteries (5V4, 12V) and resistors (10Ω, 20Ω, 40Ω, and 50Ω) connected in series.
   c. Batteries (5V, 9V, and 12V) and resistors (10Ω, 20Ω, and 30Ω) connected in series.

14. What is the maximum resistance possible given a resistor of 100 and a resistor of $40\ \Omega$?
   a. $100\ \Omega$
   b. $140\ \Omega$
   c. $180\ \Omega$
   d. $240\ \Omega$

15. Rank the points A, B, C, and D in the circuit diagram from lowest voltage to highest voltage.



a. A, B, C, D
b. B, C, A, D
c. C, B, A, D
d. D, A, B, C

19.3 Parallel Circuits

16. Can all resistor combinations be reduced to series and parallel combinations?
   a. No, all practical resistor circuits cannot be reduced to series and parallel combinations.
   b. Yes, all practical resistor circuits can be reduced to series and parallel combinations.

17. What is the equivalent resistance of the circuit shown below?

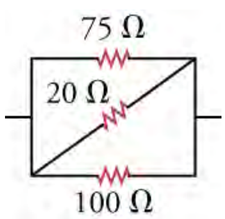


Figure 19.23

   a. The equivalent resistance of the circuit 14 Ω.
   b. The equivalent resistance of the circuit 16.7 Ω.
   c. The equivalent resistance of the circuit 140 Ω.
   d. The equivalent resistance of the circuit 195 Ω.

19.4 Electric Power

18. Two lamps have different resistances. (a) If the lamps are connected in parallel, which one is brighter, the lamp with greater resistance or the lamp with less resistance? (b) If the lamps are connected in series, which one is brighter? Note that the brighter lamp dissipates more power.
   a. (a) lamp with greater resistance; (b) lamp with less resistance
   b. (a) lamp with greater resistance; (b) lamp with greater resistance
   c. (a) lamp with less resistance; (b) lamp with less resistance
   d. (a) lamp with less resistance; (b) lamp with greater resistance

19. To measure the power consumed by your laptop computer, you place an ammeter (a device that measures electric current) in series with its DC power supply. When the screen is off, the computer draws 0.40 A of current.
When the screen is on at full brightness, it draws 0.90 A of current. Knowing the DC power supply delivers 16 V, how much power is used by the screen?
   a. The power used by the screen is –8.0 W.
   b. The power used by the screen is 0.3 W.
   c. The power used by the screen is 3.2 W.
   d. The power used by the screen is 8.0 W.

Problems

19.1 Ohm's law

20. What voltage is needed to make 6 C of charge traverse a 100-Ω resistor in 1 min?
   a. The required voltage is 1×10^{-3} V.
   b. The required voltage is 10 V.
   c. The required voltage is 1,000 V.
   d. The required voltage is 10,000 V.

21. Resistors typically obey Ohm's law at low currents, but show deviations at higher currents because of heating. Suppose you were to conduct an experiment measuring the voltage, *V*, across a resistor as a function of current, *I*, including currents whose deviations from Ohm's law start to become apparent. For a data plot of *V* versus *I*, which of the following functions would be best to fit the data? Assume that *a*, *b*, and *c* are nonzero constants adjusted to fit the data.
   a. $V = aI$
   b. $V = aI + b$
   c. $V = aI + bI^2$
   d. $V = aI + bI^2 + c$

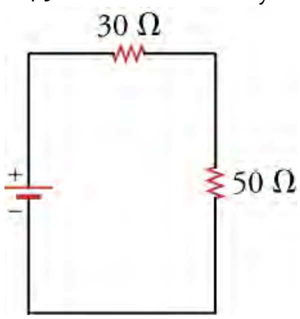
22. A battery of unknown voltage V_1 is attached across a resistor R_1. You add a second battery with $V_2 = 9.0$ V in series with V_1 so that the voltage across R_1 is now $V_1 + V_2$ and measure 0.3 A of current through resistor R_1. You add a third battery with $V_3 = 9.0$ V in series with the first two batteries so that the voltage across R_3 is $V_1 + V_2 + V_3$ and measure 0.4 A of current through R_1. What is the resistance of R_1?

a. 23.25 Ω
b. 21.75 Ω
c. 31.33 Ω
d. 13.0 Ω

19.2 Series Circuits

23. What is the voltage drop across two 80-Ω resistors connected in series with 0.15 A flowing through them?
a. 12 V
b. 24 V
c. 36 V
d. 48 V

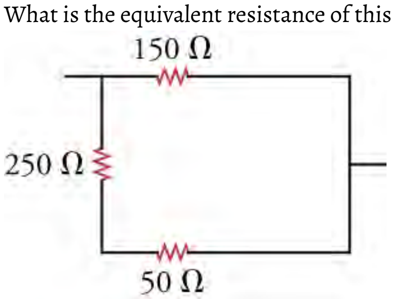
24. In this circuit, the voltage drop across the upper resistor is 4.5 V. What is the battery voltage?



a. 4.5V
b. 7.5V
c. 12V
d. 18V

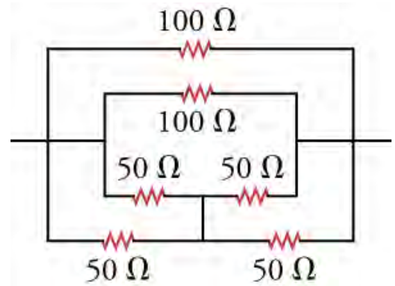
19.3 Parallel Circuits

25. What is the equivalent resistance of this circuit?



a. The equivalent resistance of the circuit is 32.7 Ω.
b. The equivalent resistance of the circuit is 100 Ω.
c. The equivalent resistance of the circuit is 327 Ω.
d. The equivalent resistance of the circuit is 450 Ω.

26. What is the equivalent resistance of the circuit shown below?



a. The equivalent resistance is 25 Ω.
b. The equivalent resistance is 50 Ω.
c. The equivalent resistance is 75 Ω.
d. The equivalent resistance is 100 Ω.

19.4 Electric Power

27. When 12 V are applied across a resistor, it dissipates 120 W of power. What is the current through the resistor?
a. The current is 1,440 A.
b. The current is 10 A.
c. The current is 0.1 A.
d. The current is 0.01 A.

28. Warming 1 g of water requires 1 J of energy per . How long would it take to warm 1 L of water from 20 to 40 °C if you immerse in the water a 1-kW resistor connected across a 9.0-V batteries aligned in series?
a. 10 min
b. 20 min
c. 30 min
d. 40 min

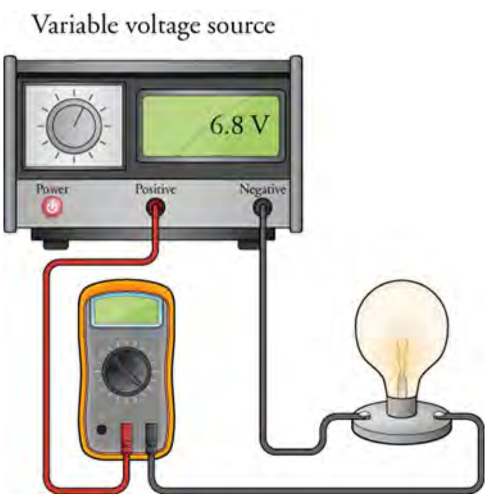
Performance Task

19.4 Electric Power

29. 1. An incandescent light bulb (i.e., an old-fashioned light bulb with a little wire in it)
2. A lightbulb socket to hold the light bulb
3. A variable voltage source
4. An ammeter

Procedure

- Screw the lightbulb into its socket. Connect the positive terminal of the voltage source to the input of the ammeter. Connect the output of the ammeter to one connection of the socket. Connect the other connection of the socket to the negative terminal of the voltage source. Ensure that the voltage source is set to supply DC voltage and that the ammeter is set to measure DC amperes. The desired circuit is shown below.



- On a piece of paper, make a two-column table with 10 rows. Label the left column *volts* and the right column *current*. Adjust the voltage source so that it supplies from between 1 and 10 volts DC. For each voltage, write the voltage in the volts column and the corresponding amperage measured by the ammeter in the current column. Make a plot of volts versus current, that is, a plot with volts on the vertical axis and current on the horizontal axis. Use this data and the plot to answer the following questions:

1. What is the resistance of the lightbulb?
2. What is the range of possible error in your result for the resistance?
3. In a single word, how would you describe the curve formed by the data points?

TEST PREP

Multiple Choice

19.1 Ohm's law

30. What are the SI units for electric current?

a. C/s
b. e/s
c. −e/s
d. C/s^2

31. What is the SI unit for resistance?

a. C/m
b. C/s
c. Ω
d. Ψ

32. The equivalent unit for an ohm is a ________.

a. V/A
b. C/m
c. $\frac{A}{V}$
d. V/s

33. You put $9.0\ \mathrm{V}$ DC across resistor R_1 and measure the current through it. With the same voltage across resistor R_2, you measure twice the current. What is the ratio $\frac{R_1}{R_2}$?

a. 1
b. $\frac{1}{2}$
c. 4
d. 2

19.2 Series Circuits

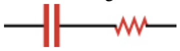
34. What does the circuit element shown represent?

a. a battery
b. a capacitor
c. the ground
d. a switch

35. How many 10-Ω resistors must be connected in series to make an equivalent resistance of 80 Ω?

a. 80
b. 8
c. 20
d. 40

36. Which two circuit elements are represented in the circuit diagram?



a. a battery connected in series with an inductor
b. a capacitor connected in series with a resistor
c. a resistor connected in series with a battery
d. an inductor connected in series with a resistor

37. How much current will flow through a 10-V battery with a 100-Ω resistor connected across its terminals?

a. 0.1 A
b. 1.0 A
c. 0
d. 1,000 A

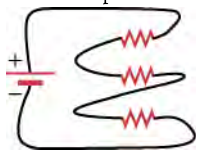
19.3 Parallel Circuits

38. A 10-Ω resistor is connected in parallel to another resistor R . The equivalent resistance of the pair is 8 Ω. What is the resistance R?

a. 10 Ω
b. 20 Ω
c. 30 Ω

d. 40 Ω

39. Are the resistors shown connected in parallel or in series? Explain.



a. The resistors are connected in parallel because the same current flows through all three resistors.
b. The resistors are connected in parallel because different current flows through all three resistors.
c. The resistors are connected in series because the same current flows through all three resistors.
d. The resistors are connected in series because different current flows through all three resistors.

19.4 Electric Power

40. Which equation below for electric power is incorrect?
a. $P = I^2 R$
b. $P = \frac{V}{R^2}$
c. $P = IV$
d. $P = \frac{V^2}{R}$

41. What power is dissipated in a circuit through which 0.12 A flows across a potential drop of 3.0 V?
a. 0.36 W
b. 0.011 W
c. Voltage drop across is 5 V.
d. 2.5 W

42. How does a resistor dissipate power?
a. A resistor dissipates power in the form of heat.
b. A resistor dissipates power in the form of sound.
c. A resistor dissipates power in the form of light.
d. A resistor dissipates power in the form of charge.

43. What power is dissipated in a circuit through which 0.12 A flows across a potential drop of 3.0 V?
a. 0.36 W
b. 0.011 W
c. 5 V
d. 2.5 W

Short Answer

19.1 Ohm's law

44. True or false—it is possible to produce nonzero DC current by adding together AC currents.
a. false
b. true

45. What type of current is used in cars?
a. alternating current
b. indirect current
c. direct current
d. straight current

46. If current were represented by C, voltage by B, and resistance by g, what would the mathematical expression be for Ohm's law?
a. $C = Bg$
b. $g = BC$
c. $\frac{B}{C} = \frac{C}{g}$
d. $B = Cg$

47. Give a verbal expression for Ohm's law.
a. Ohm's law says that the current through a resistor equals the voltage across the resistor multiplied by the resistance of the resistor.
b. Ohm's law says that the voltage across a resistor equals the current through the resistor multiplied by the resistance of the resistor.
c. Ohm's law says that the resistance of the resistor equals the current through the resistor multiplied by the voltage across a resistor.
d. Ohm's law says that the voltage across a resistor equals the square of the current through the resistor multiplied by the resistance of the resistor.

48. What is the current through a 100-Ω resistor with 12 V across it?
a. 0
b. 0.12 A
c. 8.33 A
d. 1,200 A

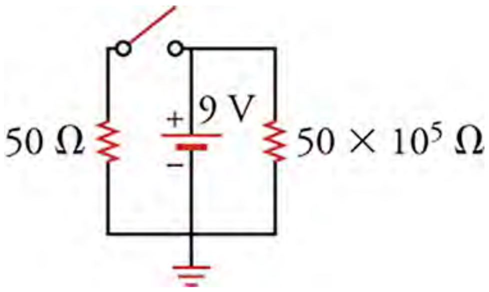
49. What resistance is required to produce 0.15 A from a 9.0 V battery?
a. 0.017
b. 1
c. 60
d. 120

19.2 Series Circuits

50. Given a circuit with one 9-V battery and with its negative terminal connected to ground. The two paths are connected to ground from the positive terminal: the right path with a 20-Ω and a 100-Ω resistor and the left path with a 50-Ω resistor. How much current will flow in the right branch?
a. $\frac{9}{120}$
b. $\frac{9}{100}$

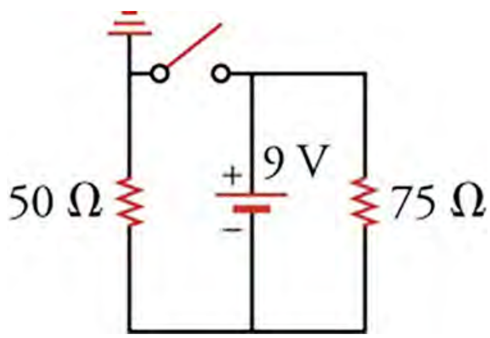
c. $\frac{9}{50}$
d. $\frac{9}{20}$

51. Through which branch in the circuit below does the most current flow?



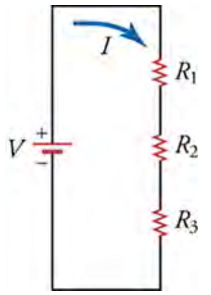
a. All of the current flows through the left branch due to the open switch.
b. All of the current flows through the right branch due to the open switch in the left branch.
c. All of the current flows through the middle branch due to the open switch in the left branch
d. There will be no current in any branch of the circuit due to the open switch.

52. What current flows through the 75-Ω resistor in the circuit below?



a. 0.072 A
b. 0.12 A
c. 0.18 A
d. 0.3 A

53. What is the equivalent resistance for the circuit below if $V = 9.0$ V and $I = 0.25$ A?



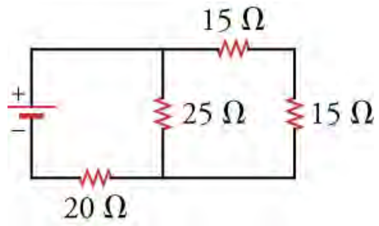
a. 0.028 Ω
b. 2.25 Ω
c. 36 Ω
d. 72 Ω

19.3 Parallel Circuits

54. Ten 100-Ω resistors are connected in series. How can you increase the total resistance of the circuit by about 40 percent?
a. Adding two 10-Ω resistors increases the total resistance of the circuit by about 40 percent.
b. Removing two 10-Ω resistors increases the total resistance of the circuit by about 40 percent.
c. Adding four 10-Ω resistors increases the total resistance of the circuit by about 40 percent.
d. Removing four 10-Ω resistors increases the total resistance of the circuit by about 40 percent.

55. Two identical resistors are connected in parallel across the terminals of a battery. If you increase the resistance of one of the resistors, what happens to the current through and the voltage across the other resistor?
a. The current and the voltage remain the same.
b. The current decreases and the voltage remains the same.
c. The current and the voltage increases.
d. The current increases and the voltage remains the same.

56.



In the circuit below, through which resistor(s) does the most current flow? Through which does the least flow? Explain.
a. The most current flows through the 15-Ω resistor because all the current must pass through this resistor.
b. The most current flows through the 20-Ω resistor because all the current must pass through this resistor.
c. The most current flows through the 25-Ω resistor because it is the highest resistance.
d. The same current flows through the all the resistor because all the current must pass through each of the resistors.

19.4 Electric Power

57. You want to increase the power dissipated in a circuit.

You have the choice between doubling the current or doubling the resistance, with the voltage remaining constant. Which one would you choose?
a. doubling the resistance
b. doubling the current

58. You want to increase the power dissipated in a circuit. You have the choice between reducing the voltage or reducing the resistance, with the current remaining constant. Which one would you choose?
a. reduce the voltage to increase the power
b. reduce the resistance to increase the power

59. What power is dissipated in the circuit consisting of 310-Ω resistors connected in series across a 9.0-V battery?
a. The power dissipated is 2430 W.
b. The power dissipated is 270 W.
c. The power dissipated is 2.7 W.
d. The power dissipated is 0.37 W.

60. What power is dissipated in a circuit consisting of three 10-Ω resistors connected in parallel across a 9.0-V battery?
a. The power dissipated is 270 W.
b. The power dissipated is 30 W.
c. The power dissipated is 24 W.
d. The power dissipated is 1/24 W.

Extended Response

19.1 Ohm's law

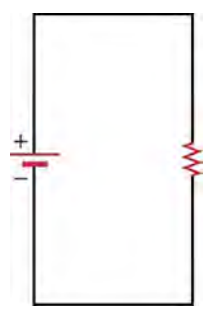
61. Describe the relationship between current and charge. Include an explanation of how the direction of the current is defined.
a. Electric current is the charge that passes through a conductor per unit time. The direction of the current is defined to be the direction in which positive charge would flow.
b. Electric current is the charges that move in a conductor. The direction of the current is defined to be the direction in which positive charge would flow.
c. Electric current is the charge that passes through a conductor per unit time. The direction of the current is defined to be the direction in which negative charge would flow.
d. Electric current is the charges that move in a conductor. The direction of the current is defined to be the direction in which negative charge would flow.

62. What could cause Ohm's law to break down?
a. If small amount of current flows through a resistor, the resistor will heat up so much that it will change state, in violation of Ohm's law.
b. If excessive amount of current flows through a resistor, the resistor will heat up so much that it will change state, in violation of Ohm's law.
c. If small amount of current flows through a resistor, the resistor will not heat up so much and it will not change its state, in violation of Ohm's law.
d. If excessive amount of current flows through a resistor, the resistor will heat up so much that it will not change its state, in violation of Ohm's law.

63. You connect a single resistor R across a 10-V battery and find that $0.01\ \text{A}$ flows through the circuit. You add another resistor R after the first resistor and find that $0.005\ \text{A}$ flows through the circuit. If you have 10 resistors R connected in a line one after the other, what would be their total resistance?
a. $\frac{R}{10}$
b. $5\,\text{R}$
c. $\frac{10}{R}$
d. $10\,\text{R}$

19.2 Series Circuits

64. Explain why the current is the same at all points in the circuit below.

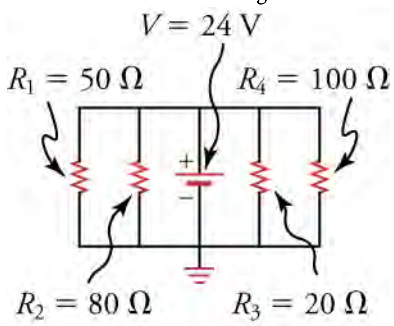


a. If the current were not constant, the mobile charges would bunch up in places, which means that the voltage would decrease at that point. A lower voltage at some point would push the current in the direction that further decreases the voltage.
b. If the current were not constant, the mobile charges would bunch up in places, which means that the voltage would increase at that point. But a higher voltage at some point would push the current in the direction that decreases the voltage.
c. If the current were not constant, the mobile charges would bunch up in places, which mean that the voltage would increase at that point. A higher voltage at some point would push the current in the direction that further increases the

voltage.

d. If the current were not constant, the mobile charges would bunch up in places, which mean that the voltage would decrease at that point. But a lower voltage at some point would push the current in the direction that increases the voltage.

65. What is the current through each resistor in the circuit?



a. Current through resistors R_1, R_2, R_3, and R_4 is 0.48 A, 0.30 A, 1.2 A, and 0.24 A, respectively.
b. Current through resistors R_1, R_2, R_3, and R_4 is 1200 A, 1920 A, 480 A, and 2400 A, respectively.
c. Current through resistors R_1, R_2, R_3, and is R_4 2.08 A, 3.34 A, 0.833 A, and 4.17 A, respectively.
d. The same amount of current, 0.096 A, flows through all of the resistors.

19.3 Parallel Circuits

66. In a house, a single incoming wire at a high potential with respect to the ground provides electric power. How are the appliances connected between this wire and the ground, in parallel or in series? Explain.

a. The appliances are connected in parallel to provide different voltage differences across each appliance.
b. The appliances are connected in parallel to provide the same voltage difference across each appliance.
c. The appliances are connected in series to provide the same voltage difference across each appliance.
d. The appliances are connected in series to provide different voltage differences across each appliance.

19.4 Electric Power

67. A single resistor is connected across the terminals of a battery When you attach a second resistor in parallel with the first, does the power dissipated by the system change?

a. No, the power dissipated remain same.
b. Yes, the power dissipated increases.
c. Yes, the power dissipated decreases.

68. In a flashlight, the batteries are normally connected in series. Why are they not connected in parallel?

a. Batteries are connected in series for higher voltage and power output.
b. Batteries are connected in series for lower voltage and power output.
c. Batteries are connected in series so that power output is a much lower for the same amount of voltage.
d. Batteries are connected in series to reduce the overall loss of energy from the circuit.

CHAPTER 20

Magnetism

Figure 20.1 The magnificent spectacle of the Aurora Borealis, or northern lights, glows in the northern sky above Bear Lake near Eielson Air Force Base, Alaska. Shaped by Earth's magnetic field, this light is produced by radiation spewed from solar storms. (credit: Senior Airman Joshua Strang, Flickr)

Chapter Outline

20.1 Magnetic Fields, Field Lines, and Force

20.2 Motors, Generators, and Transformers

20.3 Electromagnetic Induction

INTRODUCTION You may have encountered magnets for the first time as a small child playing with magnetic toys or refrigerator magnets. At the time, you likely noticed that two magnets that repulse each other will attract each other if you flip one of them around. The force that acts across the air gaps between magnets is the same force that creates wonders such as the Aurora Borealis. In fact, magnetic effects pervade our lives in myriad ways, from electric motors to medical imaging and computer memory. In this chapter, we introduce magnets and learn how they work and how magnetic fields and electric currents interact.

20.1 Magnetic Fields, Field Lines, and Force

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Summarize properties of magnets and describe how some nonmagnetic materials can become magnetized
- Describe and interpret drawings of magnetic fields around permanent magnets and current-carrying wires
- Calculate the magnitude and direction of magnetic force in a magnetic field and the force on a current-carrying wire in a magnetic field

Section Key Terms

Curie temperature	domain	electromagnet	electromagnetism	ferromagnetic
magnetic dipole	magnetic field	magnetic pole	magnetized	north pole
permanent magnet	right-hand rule	solenoid	south pole	

Magnets and Magnetization

People have been aware of magnets and magnetism for thousands of years. The earliest records date back to ancient times, particularly in the region of Asia Minor called Magnesia—the name of this region is the source of words like *magnet*. Magnetic rocks found in Magnesia, which is now part of western Turkey, stimulated interest during ancient times. When humans first discovered magnetic rocks, they likely found that certain parts of these rocks attracted bits of iron or other magnetic rocks more strongly than other parts. These areas are called the *poles* of a magnet. A **magnetic pole** is the part of a magnet that exerts the strongest force on other magnets or magnetic material, such as iron. For example, the poles of the bar magnet shown in Figure 20.2 are where the paper clips are concentrated.

Figure 20.2 A bar magnet with paper clips attracted to the two poles.

If a bar magnet is suspended so that it rotates freely, one pole of the magnet will always turn toward the north, with the opposite pole facing south. This discovery led to the compass, which is simply a small, elongated magnet mounted so that it can rotate freely. An example of a compass is shown Figure 20.3. The pole of the magnet that orients northward is called the **north pole**, and the opposite pole of the magnet is called the **south pole**.

Figure 20.3 A compass is an elongated magnet mounted in a device that allows the magnet to rotate freely.

The discovery that one particular pole of a magnet orients northward, whereas the other pole orients southward allowed people to identify the north and south poles of any magnet. It was then noticed that the north poles of two different magnets repel each other, and likewise for the south poles. Conversely, the north pole of one magnet attracts the south pole of other magnets. This situation is analogous to that of electric charge, where like charges repel and unlike charges attract. In magnets, we simply replace charge with *pole*: Like poles repel and unlike poles attract. This is summarized in Figure 20.4, which shows how the force between magnets depends on their relative orientation.

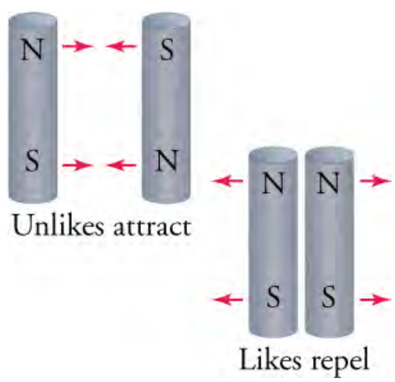


Figure 20.4 Depending on their relative orientation, magnet poles will either attract each other or repel each other.

Consider again the fact that the pole of a magnet that orients northward is called the north pole of the magnet. If unlike poles attract, then the magnetic pole of Earth that is close to the geographic North Pole must be a magnetic south pole! Likewise, the magnetic pole of Earth that is close to the geographic South Pole must be a magnetic north pole. This situation is depicted in Figure 20.5, in which Earth is represented as containing a giant internal bar magnet with its magnetic south pole at the geographic North Pole and vice versa. If we were to somehow suspend a giant bar magnet in space near Earth, then the north pole of the space magnet would be attracted to the south pole of Earth's internal magnet. This is in essence what happens with a compass needle: Its magnetic north pole is attracted to the magnet south pole of Earth's internal magnet.

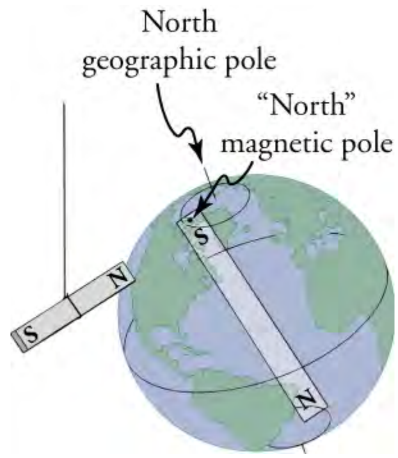


Figure 20.5 Earth can be thought of as containing a giant magnet running through its core. The magnetic south pole of Earth's magnet is at the geographic North Pole, so the north pole of magnets is attracted to the North Pole, which is how the north pole of magnets got their name. Likewise, the south pole of magnets is attracted to the geographic South Pole of Earth.

What happens if you cut a bar magnet in half? Do you obtain one magnet with two south poles and one magnet with two north poles? The answer is no: Each half of the bar magnet has a north pole and a south pole. You can even continue cutting each piece of the bar magnet in half, and you will always obtain a new, smaller magnet with two opposite poles. As shown in Figure 20.6, you can continue this process down to the atomic scale, and you will find that even the smallest particles that behave as magnets have two opposite poles. In fact, no experiment has ever found any object with a single magnetic pole, from the smallest subatomic particle such as electrons to the largest objects in the universe such as stars. Because magnets always have two poles, they are referred to as **magnetic dipoles**—*di* means *two*. Below, we will see that magnetic dipoles have properties that are analogous to electric dipoles.

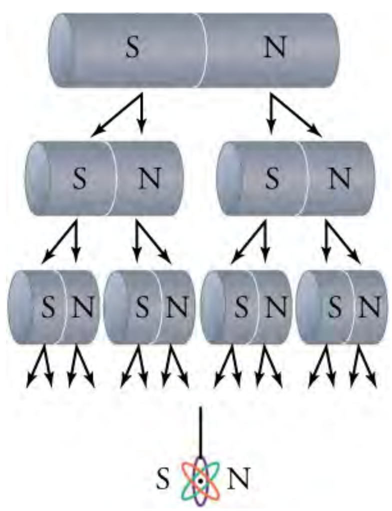


Figure 20.6 All magnets have two opposite poles, from the smallest, such as subatomic particles, to the largest, such as stars.

WATCH PHYSICS

Introduction to Magnetism

This video provides an interesting introduction to magnetism and discusses, in particular, how electrons around their atoms contribute to the magnetic effects that we observe.

Click to view content (https://www.openstax.org/l/28_intro_magn)

GRASP CHECK

Toward which magnetic pole of Earth is the north pole of a compass needle attracted?

a. The north pole of a compass needle is attracted to the north magnetic pole of Earth, which is located near the geographic North Pole of Earth.
b. The north pole of a compass needle is attracted to the south magnetic pole of Earth, which is located near the geographic North Pole of Earth.
c. The north pole of a compass needle is attracted to the north magnetic pole of Earth, which is located near the geographic South Pole of Earth.
d. The north pole of a compass needle is attracted to the south magnetic pole of Earth, which is located near the geographic South Pole of Earth.

Only certain materials, such as iron, cobalt, nickel, and gadolinium, exhibit strong magnetic effects. Such materials are called **ferromagnetic**, after the Latin word *ferrum* for iron. Other materials exhibit weak magnetic effects, which are detectable only with sensitive instruments. Not only do ferromagnetic materials respond strongly to magnets—the way iron is attracted to magnets—but they can also be **magnetized** themselves—that is, they can be induced to be magnetic or made into permanent magnets (Figure 20.7). A **permanent magnet** is simply a material that retains its magnetic behavior for a long time, even when exposed to demagnetizing influences.

Figure 20.7 An unmagnetized piece of iron is placed between two magnets, heated, and then cooled, or simply tapped when cold. The iron becomes a permanent magnet with the poles aligned as shown: Its south pole is adjacent to the north pole of the original magnet, and its north pole is adjacent to the south pole of the original magnet. Note that attractive forces are created between the central magnet and the outer magnets.

When a magnet is brought near a previously unmagnetized ferromagnetic material, it causes local magnetization of the material with unlike poles closest, as in the right side of Figure 20.7. This causes an attractive force, which is why unmagnetized iron is attracted to a magnet.

What happens on a microscopic scale is illustrated in Figure 7(a). Regions within the material called **domains** act like small bar magnets. Within domains, the magnetic poles of individual atoms are aligned. Each atom acts like a tiny bar magnet. Domains are small and randomly oriented in an unmagnetized ferromagnetic object. In response to an external magnetic field, the domains may grow to millimeter size, aligning themselves, as shown in Figure 7(b). This induced magnetization can be made permanent if the material is heated and then cooled, or simply tapped in the presence of other magnets.

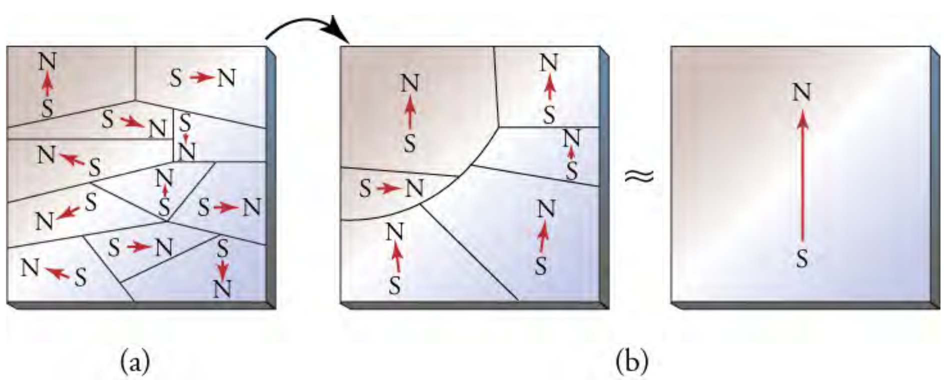


Figure 20.8 (a) An unmagnetized piece of iron—or other ferromagnetic material—has randomly oriented domains. (b) When magnetized by an external magnet, the domains show greater alignment, and some grow at the expense of others. Individual atoms are aligned within

domains; each atom acts like a tiny bar magnet.

Conversely, a permanent magnet can be demagnetized by hard blows or by heating it in the absence of another magnet. Increased thermal motion at higher temperature can disrupt and randomize the orientation and size of the domains. There is a well-defined temperature for ferromagnetic materials, which is called the **Curie temperature**, above which they cannot be magnetized. The Curie temperature for iron is 1,043 K (770 $^{\circ}\mathrm{C}$), which is well above room temperature. There are several elements and alloys that have Curie temperatures much lower than room temperature and are ferromagnetic only below those temperatures.

Snap Lab

Refrigerator Magnets

We know that like magnetic poles repel and unlike poles attract. See if you can show this for two refrigerator magnets. Will the magnets stick if you turn them over? Why do they stick to the refrigerator door anyway? What can you say about the magnetic properties of the refrigerator door near the magnet? Do refrigerator magnets stick to metal or plastic spoons? Do they stick to all types of metal?

GRASP CHECK

You have one magnet with the north and south poles labeled. How can you use this magnet to identify the north and south poles of other magnets?

a. If the north pole of a known magnet is repelled by a pole of an unknown magnet on bringing them closer, that pole of unknown magnet is its north pole; otherwise, it is its south pole.
b. If the north pole of known magnet is attracted to a pole of an unknown magnet on bringing them closer, that pole of unknown magnet is its north pole; otherwise, it is its south pole.

Magnetic Fields

We have thus seen that forces can be applied between magnets and between magnets and ferromagnetic materials without any contact between the objects. This is reminiscent of electric forces, which also act over distances. Electric forces are described using the concept of the electric field, which is a force field around electric charges that describes the force on any other charge placed in the field. Likewise, a magnet creates a **magnetic field** around it that describes the force exerted on other magnets placed in the field. As with electric fields, the pictorial representation of magnetic field lines is very useful for visualizing the strength and direction of the magnetic field.

As shown in Figure 20.9, the direction of magnetic field lines is defined to be the direction in which the north pole of a compass needle points. If you place a compass near the north pole of a magnet, the north pole of the compass needle will be repelled and point away from the magnet. Thus, the magnetic field lines point away from the north pole of a magnet and toward its south pole.

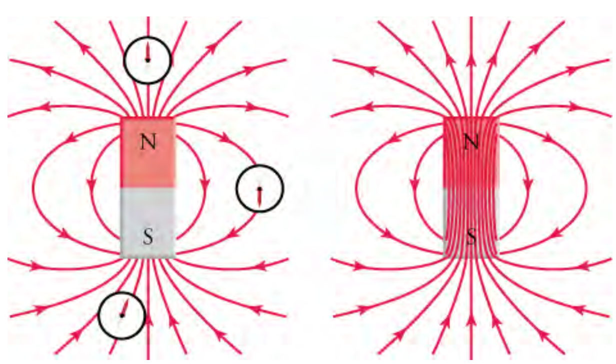


Figure 20.9 The black lines represent the magnetic field lines of a bar magnet. The field lines point in the direction that the north pole of a small compass would point, as shown at left. Magnetic field lines never stop, so the field lines actually penetrate the magnet to form complete loops, as shown at right.

Magnetic field lines can be mapped out using a small compass. The compass is moved from point to point around a magnet, and at each point, a short line is drawn in the direction of the needle, as shown in Figure 20.10. Joining the lines together then reveals the path of the magnetic field line. Another way to visualize magnetic field lines is to sprinkle iron filings around a magnet. The filings will orient themselves along the magnetic field lines, forming a pattern such as that shown on the right in Figure 20.10.

Virtual Physics

Using a Compass to Map Out the Magnetic Field

Click to view content (http://www.openstax.org/l/28magcomp)

This simulation presents you with a bar magnet and a small compass. Begin by dragging the compass around the bar magnet to see in which direction the magnetic field points. Note that the strength of the magnetic field is represented by the brightness of the magnetic field icons in the grid pattern around the magnet. Use the magnetic field meter to check the field strength at several points around the bar magnet. You can also flip the polarity of the magnet, or place Earth on the image to see how the compass orients itself.

GRASP CHECK

With the slider at the top right of the simulation window, set the magnetic field strength to 100 percent . Now use the magnetic field meter to answer the following question: Near the magnet, where is the magnetic field strongest and where is it weakest? Don't forget to check inside the bar magnet.

a. The magnetic field is strongest at the center and weakest between the two poles just outside the bar magnet. The magnetic field lines are densest at the center and least dense between the two poles just outside the bar magnet.
b. The magnetic field is strongest at the center and weakest between the two poles just outside the bar magnet. The magnetic field lines are least dense at the center and densest between the two poles just outside the bar magnet.
c. The magnetic field is weakest at the center and strongest between the two poles just outside the bar magnet. The magnetic field lines are densest at the center and least dense between the two poles just outside the bar magnet.
d. The magnetic field is weakest at the center and strongest between the two poles just outside the bar magnet and the magnetic field lines are least dense at the center and densest between the two poles just outside the bar magnet.

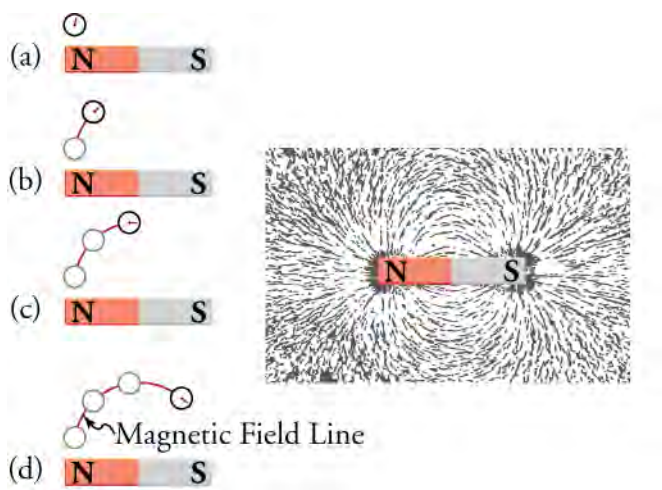


Figure 20.10 Magnetic field lines can be drawn by moving a small compass from point to point around a magnet. At each point, draw a short line in the direction of the compass needle. Joining the points together reveals the path of the magnetic field lines. Another way to visualize magnetic field lines is to sprinkle iron filings around a magnet, as shown at right.

When two magnets are brought close together, the magnetic field lines are perturbed, just as happens for electric field lines when two electric charges are brought together. Bringing two north poles together—or two south poles—will cause a repulsion, and the magnetic field lines will bend away from each other. This is shown in Figure 20.11, which shows the magnetic field lines created by the two closely separated north poles of a bar magnet. When opposite poles of two magnets are brought together, the magnetic field lines join together and become denser between the poles. This situation is shown in Figure 20.11.

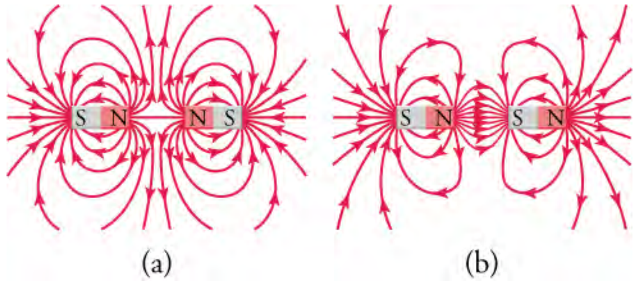


Figure 20.11 (a) When two north poles are approached together, the magnetic field lines repel each other and the two magnets experience a repulsive force. The same occurs if two south poles are approached together. (b) If opposite poles are approached together, the magnetic field lines become denser between the poles and the magnets experience an attractive force.

Like the electric field, the magnetic field is stronger where the lines are denser. Thus, between the two north poles in Figure 20.11, the magnetic field is very weak because the density of the magnetic field is almost zero. A compass placed at that point would essentially spin freely if we ignore Earth's magnetic field. Conversely, the magnetic field lines between the north and south poles in Figure 20.11 are very dense, indicating that the magnetic field is very strong in this region. A compass placed here would quickly align with the magnetic field and point toward the south pole on the right.

Note that magnets are not the only things that make magnetic fields. Early in the nineteenth century, people discovered that electrical currents cause magnetic effects. The first significant observation was by the Danish scientist Hans Christian Oersted (1777–1851), who found that a compass needle was deflected by a current-carrying wire. This was the first significant evidence that the movement of electric charges had any connection with magnets. An **electromagnet** is a device that uses electric current to make a magnetic field. These temporarily induced magnets are called electromagnets. Electromagnets are employed for everything from a wrecking yard crane that lifts scrapped cars to controlling the beam of a 90-km-circumference particle accelerator to the magnets in medical-imaging machines (see Figure 20.12).

Figure 20.12 Instrument for magnetic resonance imaging (MRI). The device uses a cylindrical-coil electromagnet to produce for the main magnetic field. The patient goes into the *tunnel* on the gurney. (credit: Bill McChesney, Flickr)

The magnetic field created by an electric current in a long straight wire is shown in Figure 20.13. The magnetic field lines form concentric circles around the wire. The direction of the magnetic field can be determined using the *right-hand rule*. This rule shows up in several places in the study of electricity and magnetism. Applied to a straight current-carrying wire, the **right-hand rule** says that, with your right thumb pointed in the direction of the current, the magnetic field will be in the direction in which your right fingers curl, as shown in Figure 20.13. If the wire is very long compared to the distance r from the wire, the strength B of the magnetic field is given by

$$B_{\text{straightwire}} = \frac{\mu_0 I}{2\pi r} \qquad (20.1)$$

where I is the current in the wire in amperes. The SI unit for magnetic field is the tesla (T). The symbol μ_0 —read "mu-zero"—is a constant called the "permeability of free space" and is given by

$$\mu_0 = 4\pi \times 10^{-7} \text{T} \cdot \text{m/A}. \qquad (20.2)$$

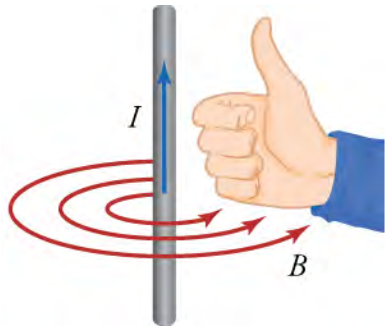


Figure 20.13 This image shows how to use the right-hand rule to determine the direction of the magnetic field created by current flowing through a straight wire. Point your right thumb in the direction of the current, and the magnetic field will be in the direction in which your fingers curl.

WATCH PHYSICS

Magnetic Field Due to an Electric Current

This video describes the magnetic field created by a straight current-carrying wire. It goes over the right-hand rule to determine the direction of the magnetic field, and presents and discusses the formula for the strength of the magnetic field due to a straight current-carrying wire.

Click to view content (https://www.openstax.org/l/28magfield)

GRASP CHECK

A long straight wire is placed on a table top and electric current flows through the wire from right to left. If you look at the wire end-on from the left end, does the magnetic field go clockwise or counterclockwise?

a. By pointing your right-hand thumb in the direction opposite of current, the right-hand fingers will curl counterclockwise, so the magnetic field will be in the counterclockwise direction.
b. By pointing your right-hand thumb in the direction opposite of current, the right-hand fingers will curl clockwise, so the magnetic field will be in the clockwise direction.
c. By pointing your right-hand thumb in the direction of current, the right-hand fingers will curl counterclockwise, so the magnetic field will be in the counterclockwise direction.
d. By pointing your right-hand thumb in the direction of current, the right-hand fingers will curl clockwise, so the magnetic field will be in the clockwise direction.

Now imagine winding a wire around a cylinder with the cylinder then removed. The result is a wire coil, as shown in Figure 20.14. This is called a **solenoid**. To find the direction of the magnetic field produced by a solenoid, apply the right-hand rule to several points on the coil. You should be able to convince yourself that, inside the coil, the magnetic field points from left to right. In fact, another application of the right-hand rule is to curl your right-hand fingers around the coil in the direction in which the current flows. Your right thumb then points in the direction of the magnetic field inside the coil: left to right in this case.

Figure 20.14 A wire coil with current running through as shown produces a magnetic field in the direction of the red arrow.

Each loop of wire contributes to the magnetic field inside the solenoid. Because the magnetic field lines must form closed loops, the field lines close the loop outside the solenoid. The magnetic field lines are much denser inside the solenoid than outside the solenoid. The resulting magnetic field looks very much like that of a bar magnet, as shown in Figure 20.15. The magnetic field strength deep inside a solenoid is

$$B_{\text{solenoid}} = \mu_0 \frac{NI}{\ell}, \tag{20.3}$$

where N is the number of wire loops in the solenoid and ℓ is the length of the solenoid.

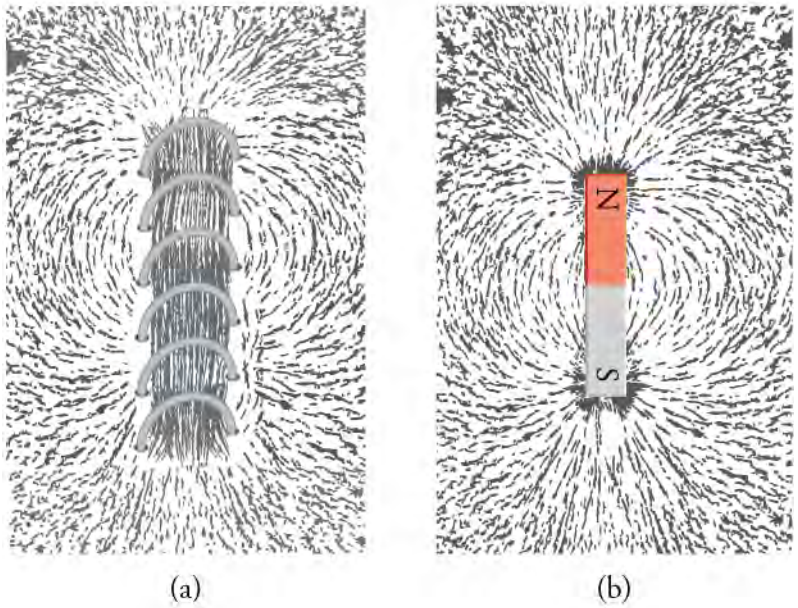


Figure 20.15 Iron filings show the magnetic field pattern around (a) a solenoid and (b) a bar magnet. The fields patterns are very similar, especially near the ends of the solenoid and bar magnet.

Virtual Physics

Electromagnets

Click to view content (http://www.openstax.org/l/28elec_magnet)

Use this simulation to visualize the magnetic field made from a solenoid. Be sure to click on the tab that says Electromagnet. You can drive AC or DC current through the solenoid by choosing the appropriate current source. Use the field meter to measure the strength of the magnetic field and then change the number of loops in the solenoid to see how this affects the magnetic field strength.

GRASP CHECK

Choose the battery as current source and set the number of wire loops to four. With a nonzero current going through the solenoid, measure the magnetic field strength at a point. Now decrease the number of wire loops to two. How does the magnetic field strength change at the point you chose?

a. There will be no change in magnetic field strength when number of loops reduces from four to two.
b. The magnetic field strength decreases to half of its initial value when number of loops reduces from four to two.
c. The magnetic field strength increases to twice of its initial value when number of loops reduces from four to two.
d. The magnetic field strength increases to four times of its initial value when number of loops reduces from four to two.

Magnetic Force

If a moving electric charge, that is electric current, produces a magnetic field that can exert a force on another magnet, then the reverse should be true by Newton's third law. In other words, a charge moving through the magnetic field produced by another object should experience a force—and this is exactly what we find. As a concrete example, consider Figure 20.16, which shows a charge q moving with velocity $\vec{v}$ through a magnetic field $\vec{B}$ between the poles of a permanent magnet. The magnitude F of the force experienced by this charge is

$$F = qvB\sin\theta, \tag{20.4}$$

where θ is the angle between the velocity of the charge and the magnetic field.

The direction of the force may be found by using another version of the right-hand rule: First, we join the tails of the velocity vector and a magnetic field vector, as shown in step 1 of Figure 20.16. We then curl our right fingers from $\vec{v}$ to $\vec{B}$, as indicated in step (2) of Figure 20.16. The direction in which the right thumb points is the direction of the force. For the charge in Figure 20.16, we find that the force is directed into the page.

Note that the factor $\sin\theta$ in the equation $F = qvB\sin\theta$ means that zero force is applied on a charge that moves parallel to a magnetic field because $\theta = 0$ and $\sin 0 = 0$. The maximum force a charge can experience is when it moves perpendicular to the magnetic field, because $\theta = 90°$ and $\sin 90° = 1$.

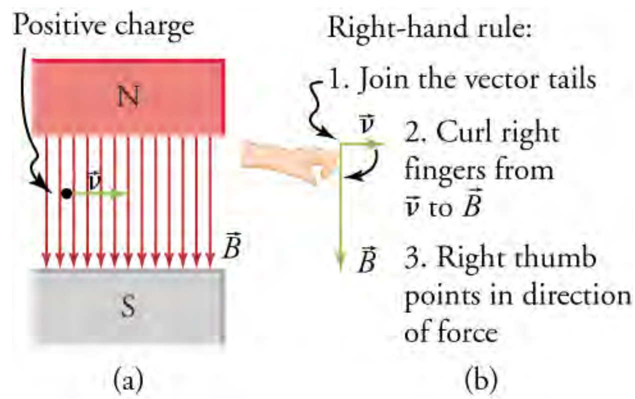


Figure 20.16 (a) An electron moves through a uniform magnetic field. (b) Using the right-hand rule, the force on the electron is found to be directed into the page.

LINKS TO PHYSICS

Magnetohydrodynamic Drive

In Tom Clancy's Cold War novel "The Hunt for Red October," the Soviet Union built a submarine (see Figure 20.17) with a magnetohydrodynamic drive that was so silent it could not be detected by surface ships. The only conceivable purpose to build such a submarine was to give the Soviet Union first-strike capability, because this submarine could sneak close to the coast of the United States and fire its ballistic missiles, destroying key military and government installations to prevent an American counterattack.

Figure 20.17 A Typhoon-class Russian ballistic-missile submarine on which the fictional submarine Red October was based.

A magnetohydrodynamic drive is supposed to be silent because it has no moving parts. Instead, it uses the force experienced by charged particles that move in a magnetic field. The basic idea behind such a drive is depicted in Figure 20.18. Salt water flows through a channel that runs from the front to the back of the submarine. A magnetic field is applied horizontally across the channel, and a voltage is applied across the electrodes on the top and bottom of the channel to force a downward electric current through the water. The charge carriers are the positive sodium ions and the negative chlorine ions of salt. Using the right-hand rule, the force on the charge carriers is found to be toward the rear of the vessel. The accelerated charges collide with water molecules and transfer their momentum, creating a jet of water that is propelled out the rear of the channel. By Newton's third law, the vessel experiences a force of equal magnitude, but in the opposite direction.

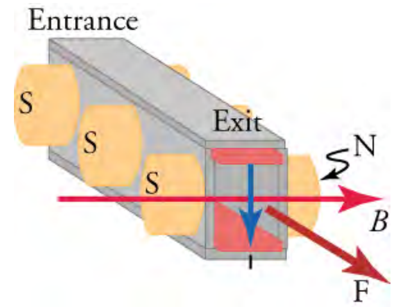


Figure 20.18 A schematic drawing of a magnetohydrodynamic drive showing the water channel, the current direction, the magnetic field direction, and the resulting force.

Fortunately for all involved, it turns out that such a propulsion system is not very practical. Some back-of-the-envelope calculations show that, to power a submarine, either extraordinarily high magnetic fields or extraordinarily high electric currents would be required to obtain a reasonable thrust. In addition, prototypes of magnetohydrodynamic drives show that they are anything but silent. Electrolysis caused by running a current through salt water creates bubbles of hydrogen and oxygen, which makes this propulsion system quite noisy. The system also leaves a trail of chloride ions and metal chlorides that can easily be detected to locate the submarine. Finally, the chloride ions are extremely reactive and very quickly corrode metal parts, such as the electrode or the water channel itself. Thus, the Red October remains in the realm of fiction, but the physics involved is quite real.

GRASP CHECK

If the magnetic field is downward, in what direction must the current flow to obtain rearward-pointing force?

a. The current must flow vertically from up to down when viewed from the rear of the boat.
b. The current must flow vertically from down to up when viewed from the rear of the boat.
c. The current must flow horizontally from left to right when viewed from the rear of the boat.
d. The current must flow horizontally from right to left when viewed from the rear of the boat.

Instead of a single charge moving through a magnetic field, consider now a steady current I moving through a straight wire. If we place this wire in a uniform magnetic field, as shown in Figure 20.19, what is the force on the wire or, more precisely, on the electrons in the wire? An electric current involves charges that move. If the charges q move a distance ℓ in a time t, then their speed is $v = \ell/t$. Inserting this into the equation $F = qvB\sin\theta$ gives

$$\begin{aligned} F &= q\left(\frac{\ell}{t}\right)B\sin\theta \\ &= \left(\frac{q}{t}\right)\ell B\sin\theta. \end{aligned} \quad (20.5)$$

The factor q/t in this equation is nothing more than the current in the wire. Thus, using $I = q/t$, we obtain

$$F = I\ell B\sin\theta(1.4). \quad (20.6)$$

This equation gives the force on a straight current-carrying wire of length ℓ in a magnetic field of strength B. The angle θ is the angle between the current vector and the magnetic field vector. Note that ℓ is the length of wire that is in the magnetic field and for which $\theta \neq 0$, as shown in Figure 20.19.

The direction of the force is determined in the same way as for a single charge. Curl your right fingers from the vector for I to the vector for B, and your right thumb will point in the direction of the force on the wire. For the wire shown in Figure 20.19, the force is directed into the page.

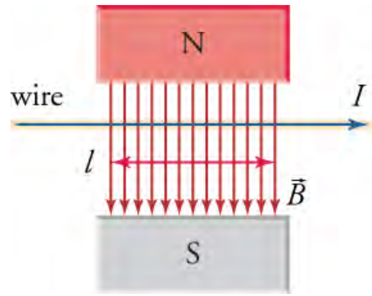


Figure 20.19 A straight wire carrying current I in a magnetic field B. The force exerted on the wire is directed into the page. The length ℓ is the length of the wire that is *in* the magnetic field.

Throughout this section, you may have noticed the symmetries between magnetic effects and electric effects. These effects all fall under the umbrella of **electromagnetism**, which is the study of electric and magnetic phenomena. We have seen that electric charges produce electric fields, and moving electric charges produce magnetic fields. A magnetic dipole produces a magnetic field, and, as we will see in the next section, moving magnetic dipoles produce an electric field. Thus, electricity and magnetism are two intimately related and symmetric phenomena.

WORKED EXAMPLE

Trajectory of Electron in Magnetic Field

A proton enters a region of constant magnetic field, as shown in Figure 20.20. The magnetic field is coming out of the page. If the electron is moving at $3.0 \times 10^6 \text{m/s}$ and the magnetic field strength is 2.0 T, what is the magnitude and direction of the force on the proton?

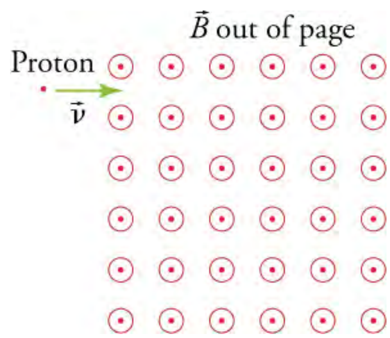


Figure 20.20 A proton enters a region of uniform magnetic field. The magnetic field is coming out of the page—the circles with dots represent vector arrow heads coming out of the page.

STRATEGY

Use the equation $F = qvB\sin\theta$ to find the magnitude of the force on the proton. The angle between the magnetic field vectors and the velocity vector of the proton is $90°$. The direction of the force may be found by using the right-hand rule.

Solution

The charge of the proton is $q = 1.60 \times 10^{-19} \text{C}$. Entering this value and the given velocity and magnetic field strength into the equation $F = qvB\sin\theta$ gives

$$\begin{aligned} F &= qvB\sin\theta \\ &= \left(1.60 \times 10^{-19} \text{C}\right)\left(3.0 \times 10^6 \text{m/s}\right)(2.0\text{ T})\sin(90°) \\ &= 9.6 \times 10^{-13}\text{N}. \end{aligned} \quad (20.7)$$

To find the direction of the force, first join the velocity vector end to end with the magnetic field vector, as shown in Figure 20.21. Now place your right hand so that your fingers point in the direction of the velocity and curl them upward toward the magnetic field vector. The force is in the direction in which your thumb points. In this case, the force is downward in the plane of the paper in the $\hat{z}$ -direction, as shown in Figure 20.21.

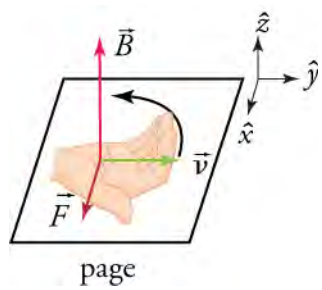


Figure 20.21 The velocity vector and a magnetic field vector from Figure 20.20 are placed end to end. A right hand is shown with the fingers curling up from the velocity vector toward the magnetic field vector. The thumb points in the direction of the resulting force, which is the $\hat{z}$ -direction in this case.

Thus, combining the magnitude and the direction, we find that the force on the proton is $\left(9.6 \times 10^{-13}\text{N}\right)\hat{z}$.

Discussion

This seems like a very small force. However, the proton has a mass of $1.67 \times 10^{-27}\text{kg}$, so its acceleration is $a = \frac{F}{m} = \frac{9.6 \times 10^{-13}\text{N}}{1.67 \times 10^{-27}\text{kg}} = 5.7 \times 10^{14}\ \text{m/s}^2$, or about ten thousand billion times the acceleration due to gravity!

We found that the proton's initial acceleration as it enters the magnetic field is downward in the plane of the page. Notice that, as the proton accelerates, its velocity remains perpendicular to the magnetic field, so the magnitude of the force does not change. In addition, because of the right-hand rule, the direction of the force remains perpendicular to the velocity. This force is nothing more than a centripetal force: It has a constant magnitude and is always perpendicular to the velocity. Thus, the magnitude of the velocity does not change, and the proton executes circular motion. The radius of this circle may be found by using the kinematics relationship.

$$\begin{aligned} F &= ma = m\frac{v^2}{r} \\ a &= \frac{v^2}{r} \\ r &= \frac{v^2}{a} = \frac{\left(3.0 \times 10^6\text{m/s}\right)^2}{5.7 \times 10^{14}\ \text{m/s}^2} = 1.6\ \text{cm} \end{aligned} \quad (20.8)$$

The path of the proton in the magnetic field is shown in Figure 20.22.

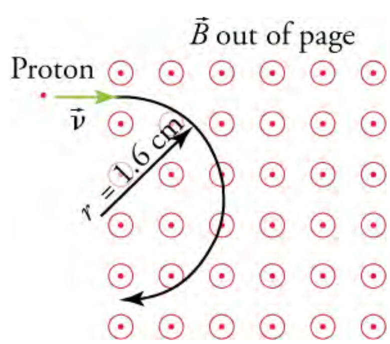
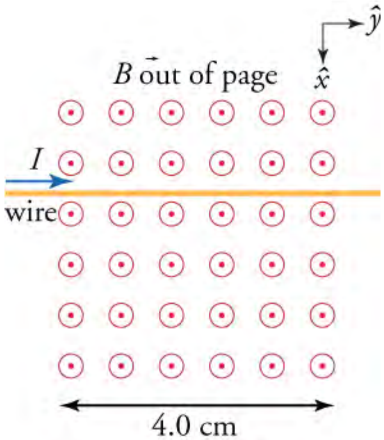


Figure 20.22 When traveling perpendicular to a constant magnetic field, a charged particle will execute circular motion, as shown here for a proton.

WORKED EXAMPLE

Wire with Current in Magnetic Field

Now suppose we run a wire through the uniform magnetic field from the previous example, as shown. If the wire carries a current of 1.0 A in the $\hat{y}$ -direction, and the region with magnetic field is 4.0 cm long, what is the force on the wire?



STRATEGY

Use equation $F = I\ell B \sin\theta$ to find the magnitude of the force on the wire. The length of the wire inside the magnetic field is 4.0 cm, and the angle between the current direction and the magnetic field direction is 90°. To find the direction of the force, use the right-hand rule as explained just after the equation $F = I\ell B \sin\theta$.

Solution

Insert the given values into equation $F = I\ell B \sin\theta$ to find the magnitude of the force

$$F = I\ell B \sin\theta = (1.5\ \text{A})\,(0.040\ \text{m})\,(2.0\ \text{T}) = 0.12\ \text{N}. \qquad (20.9)$$

To find the direction of the force, begin by placing the current vector end to end with a vector for the magnetic field. The result is as shown in the figure in the previous Worked Example with $\vec{v}$ replaced by $\vec{I}$. Curl your right-hand fingers from $\vec{I}$ to $\vec{B}$ and your right thumb points down the page, again as shown in the figure in the previous Worked Example. Thus, the direction of the force is in the $\hat{x}$ -direction. The complete force is thus $(0.12\ \text{N})\,\hat{x}$.

Discussion

The direction of the force is the same as the initial direction of the force was in the previous example for a proton. However, because the current in a wire is confined to a wire, the direction in which the charges move does not change. Instead, the entire wire accelerates in the $\hat{x}$ -direction. The force on a current-carrying wire in a magnetic field is the basis of all electrical motors, as we will see in the upcoming sections.

Practice Problems

1. What is the magnitude of the force on an electron moving at 1.0 × 106 m/s perpendicular to a 1.0-T magnetic field?
   a. 0.8×10^{-13} N
   b. 1.6×10^{-14} N
   c. 0.8×10^{-14} N
   d. 1.6×10^{-13} N

2. A straight 10 cm wire carries 0.40 A and is oriented perpendicular to a magnetic field. If the force on the wire is 0.022 N, what is the magnitude of the magnetic field?
   a. 1.10×10^{-2} T
   b. 0.55×10^{-2} T
   c. 1.10 T
   d. 0.55 T

Check Your Understanding

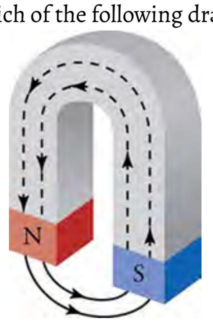
3. If two magnets repel each other, what can you conclude about their relative orientation?
   a. Either the south pole of magnet 1 is closer to the north pole of magnet 2 or the north pole of magnet 1 is closer to the south pole of magnet 2.
   b. Either the south poles of both the magnet 1 and magnet 2 are closer to each other or the north poles of both the magnet 1

and magnet 2 are closer to each other.

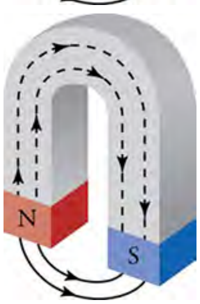
4. Describe methods to demagnetize a ferromagnet.
   a. by cooling, heating, or submerging in water
   b. by heating, hammering, and spinning it in external magnetic field
   c. by hammering, heating, and rubbing with cloth
   d. by cooling, submerging in water, or rubbing with cloth

5. What is a magnetic field?
   a. The directional lines present inside and outside the magnetic material that indicate the magnitude and direction of the magnetic force.
   b. The directional lines present inside and outside the magnetic material that indicate the magnitude of the magnetic force.
   c. The directional lines present inside the magnetic material that indicate the magnitude and the direction of the magnetic force.
   d. The directional lines present outside the magnetic material that indicate the magnitude and the direction of the magnetic force.

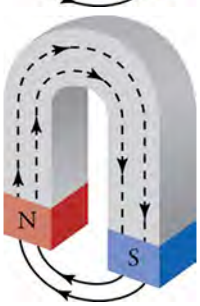
6. Which of the following drawings is correct?



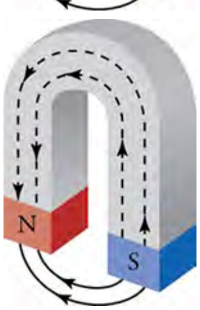
   a.



   b.



   c.



   d.

20.2 Motors, Generators, and Transformers

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain how electric motors, generators, and transformers work
- Explain how commercial electric power is produced, transmitted, and distributed

Section Key Terms

electric motor	generator	transformer

Electric Motors, Generators, and Transformers

As we learned previously, a current-carrying wire in a magnetic field experiences a force—recall $F = I\ell B \sin\theta$. **Electric motors**, which convert electrical energy into mechanical energy, are the most common application of magnetic force on current-carrying wires. Motors consist of loops of wire in a magnetic field. When current is passed through the loops, the magnetic field exerts a torque on the loops, which rotates a shaft. Electrical energy is converted to mechanical work in the process. Figure 20.23 shows a schematic drawing of an electric motor.

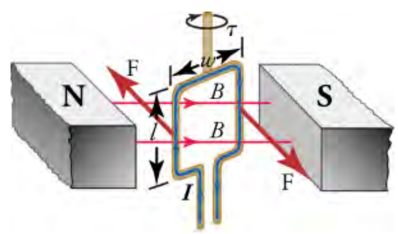


Figure 20.23 Torque on a current loop. A vertical loop of wire in a horizontal magnetic field is attached to a vertical shaft. When current is passed through the wire loop, torque is exerted on it, making it turn the shaft.

Let us examine the force on each segment of the loop in Figure 20.23 to find the torques produced about the axis of the vertical shaft—this will lead to a useful equation for the torque on the loop. We take the magnetic field to be uniform over the rectangular loop, which has width w and height ℓ, as shown in the figure. First, consider the force on the top segment of the loop. To determine the direction of the force, we use the right-hand rule. The current goes from left to right into the page, and the magnetic field goes from left to right in the plane of the page. Curl your right fingers from the current vector to the magnetic field vector and your right thumb points down. Thus, the force on the top segment is downward, which produces no torque on the shaft. Repeating this analysis for the bottom segment—neglect the small gap where the lead wires go out—shows that the force on the bottom segment is upward, again producing no torque on the shaft.

Consider now the left vertical segment of the loop. Again using the right-hand rule, we find that the force exerted on this segment is perpendicular to the magnetic field, as shown in Figure 20.23. This force produces a torque on the shaft. Repeating this analysis on the right vertical segment of the loop shows that the force on this segment is in the direction opposite that of the force on the left segment, thereby producing an equal torque on the shaft. The total torque on the shaft is thus twice the toque on one of the vertical segments of the loop.

To find the magnitude of the torque as the wire loop spins, consider Figure 20.24, which shows a view of the wire loop from above. Recall that torque is defined as $\tau = rF\sin\theta$, where F is the applied force, r is the distance from the pivot to where the force is applied, and θ is the angle between r and F. Notice that, as the loop spins, the current in the vertical loop segments is always perpendicular to the magnetic field. Thus, the equation $F = I\ell B \sin\theta$ gives the magnitude of the force on each vertical segment as $F = I\ell B$. The distance r from the shaft to where this force is applied is $w/2$, so the torque created by this force is

$$\tau_{\text{segment}} = rF\sin\theta = w/2I\ell B\sin\theta = (w/2)\,I\ell B\sin\theta. \tag{20.10}$$

Because there are two vertical segments, the total torque is twice this, or

$$\tau = wI\ell B\sin\theta. \tag{20.11}$$

If we have a multiple loop with N turns, we get N times the torque of a single loop. Using the fact that the area of the loop is $A = w\ell$; the expression for the torque becomes

$$\tau = NIAB \sin \theta. \tag{20.12}$$

This is the torque on a current-carrying loop in a uniform magnetic field. This equation can be shown to be valid for a loop of any shape.

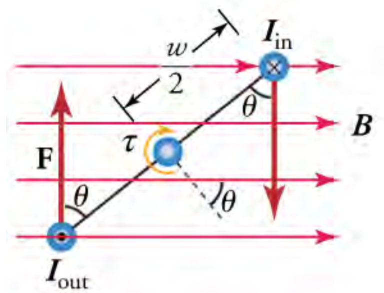


Figure 20.24 View from above of the wire loop from Figure 20.23. The magnetic field generates a force F on each vertical segment of the wire loop, which generates a torque on the shaft. Notice that the currents I_{in} and I_{out} have the same magnitude because they both represent the current flowing in the wire loop, but I_{in} flows into the page and I_{out} flows out of the page.

From the equation $\tau = NIAB \sin \theta$, we see that the torque is zero when $\theta = 0$. As the wire loop rotates, the torque increases to a maximum positive torque of $w\ell B$ when $\theta = 90°$. The torque then decreases back to zero as the wire loop rotates to $\theta = 180°$. From $\theta = 180°$ to $\theta = 360°$, the torque is negative. Thus, the torque changes sign every half turn, so the wire loop will oscillate back and forth.

For the coil to continue rotating in the same direction, the current is reversed as the coil passes through $\theta = 0$ and$\theta = 180°$ using automatic switches called *brushes*, as shown in Figure 20.25.

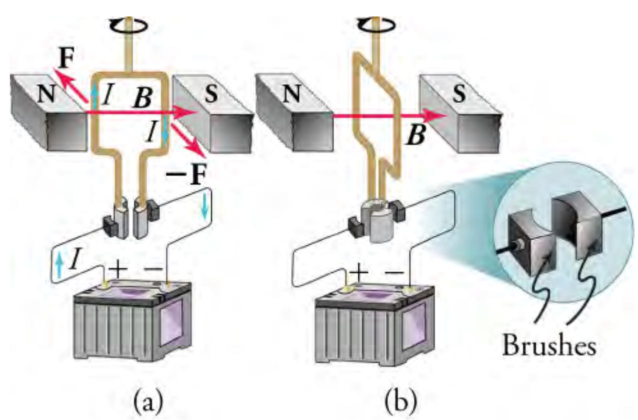


Figure 20.25 (a) As the angular momentum of the coil carries it through $\theta = 0$, the brushes reverse the current and the torque remains clockwise. (b) The coil rotates continuously in the clockwise direction, with the current reversing each half revolution to maintain the clockwise torque.

Consider now what happens if we run the motor in reverse; that is, we attach a handle to the shaft and mechanically force the coil to rotate within the magnetic field, as shown in Figure 20.26. As per the equation $F = qvB \sin \theta$—where θ is the angle between the vectors $\vec{v}$ and $\vec{B}$—charges in the wires of the loop experience a magnetic force because they are moving in a magnetic field. Again using the right-hand rule, where we curl our fingers from vector $\vec{v}$ to vector $\vec{B}$, we find that charges in the top and bottom segments feel a force perpendicular to the wire, which does not cause a current. However, charges in the vertical wires experience forces parallel to the wire, causing a current to flow through the wire and through an external circuit if one is connected. A device such as this that converts mechanical energy into electrical energy is called a **generator**.

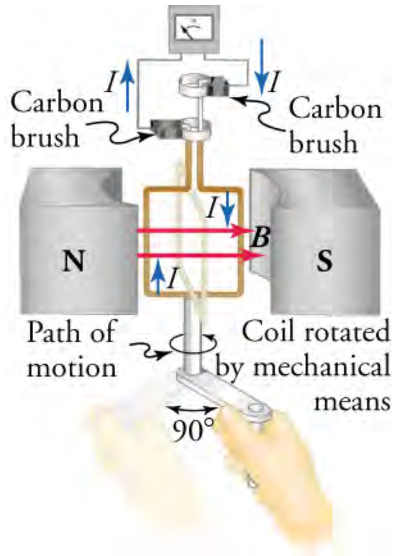


Figure 20.26 When this coil is rotated through one-fourth of a revolution, the magnetic flux Φ changes from its maximum to zero, inducing an emf, which drives a current through an external circuit.

Because current is induced only in the side wires, we can find the induced emf by only considering these wires. As explained in Induced Current in a Wire, motional emf in a straight wire moving at velocity v through a magnetic field B is $E = B\ell v$, where the velocity is perpendicular to the magnetic field. In the generator, the velocity makes an angle θ with B (see Figure 20.27), so the velocity component perpendicular to B is $v \sin\theta$. Thus, in this case, the emf induced on each vertical wire segment is $E = B\ell v \sin\theta$, and they are in the same direction. The total emf around the loop is then

$$E = 2B\ell v \sin\theta. \tag{20.13}$$

Although this expression is valid, it does not give the emf as a function of time. To find how the emf evolves in time, we assume that the coil is rotated at a constant angular velocity ω. The angle θ is related to the angular velocity by $\theta = \omega t$, so that

$$E = 2B\ell v \sin\omega t. \tag{20.14}$$

Recall that tangential velocity v is related to angular velocity ω by $v = r\omega$. Here, $r = w/2$, so that $v = (w/2)\,\omega$ and

$$E = 2B\ell\left(\frac{w}{2}\omega\right)\sin\omega t = B\ell w\omega \sin\omega t. \tag{20.15}$$

Noting that the area of the loop is $A = \ell w$ and allowing for N wire loops, we find that

$$E = NAB\omega \sin\omega t \tag{20.16}$$

is the emf induced in a generator coil of N turns and area A rotating at a constant angular velocity ω in a uniform magnetic field B. This can also be expressed as

$$E = E_0 \sin\omega t \tag{20.17}$$

where

$$E_0 = NAB\omega \tag{20.18}$$

is the maximum (peak) emf.

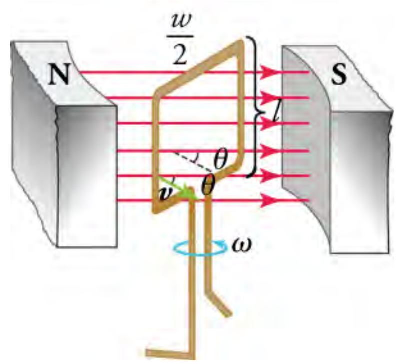


Figure 20.27 The instantaneous velocity of the vertical wire segments makes an angle θ with the magnetic field. The velocity is shown in the figure by the green arrow, and the angle θ is indicated.

Figure 20.28 shows a generator connected to a light bulb and a graph of the emf vs. time. Note that the emf oscillates from a positive maximum of E_0 to a negative maximum of $-E_0$. In between, the emf goes through zero, which means that zero current flows through the light bulb at these times. Thus, the light bulb actually flickers on and off at a frequency of 2*f*, because there are two zero crossings per period. Since alternating current such as this is used in homes around the world, why do we not notice the lights flickering on and off? In the United States, the frequency of alternating current is 60 Hz, so the lights flicker on and off at a frequency of 120 Hz. This is faster than the refresh rate of the human eye, so you don't notice the flicker of the lights. Also, other factors prevent various different types of light bulbs from switching on and off so fast, so the light output is *smoothed out* a bit.

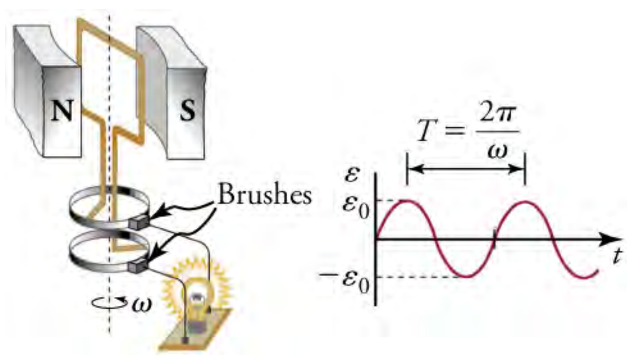


Figure 20.28 The emf of a generator is sent to a light bulb with the system of rings and brushes shown. The graph gives the emf of the generator as a function of time. E_0 is the peak emf. The period is $T = 1/f = 2\pi/\omega$, where *f* is the frequency at which the coil is rotated in the magnetic field.

Virtual Physics

Generator

Click to view content (http://www.openstax.org/l/28gen)

Use this simulation to discover how an electrical generator works. Control the water supply that makes a water wheel turn a magnet. This induces an emf in a nearby wire coil, which is used to light a light bulb. You can also replace the light bulb with a voltmeter, which allows you to see the polarity of the voltage, which changes from positive to negative.

GRASP CHECK

Set the number of wire loops to three, the bar-magnet strength to about 50 percent, and the loop area to 100 percent. Note the maximum voltage on the voltmeter. Assuming that one major division on the voltmeter is 5V, what is the maximum voltage when using only a single wire loop instead of three wire loops?

a. 5 V
b. 15 V

c. 125 V
d. 53 V

In real life, electric generators look a lot different than the figures in this section, but the principles are the same. The source of mechanical energy that turns the coil can be falling water—hydropower—steam produced by the burning of fossil fuels, or the kinetic energy of wind. Figure 20.29 shows a cutaway view of a steam turbine; steam moves over the blades connected to the shaft, which rotates the coil within the generator.

Figure 20.29 Steam turbine generator. The steam produced by burning coal impacts the turbine blades, turning the shaft which is connected to the generator. (credit: Nabonaco, Wikimedia Commons)

Another very useful and common device that exploits magnetic induction is called a **transformer**. Transformers do what their name implies—they transform voltages from one value to another; the term voltage is used rather than emf because transformers have internal resistance. For example, many cell phones, laptops, video games, power tools, and small appliances have a transformer built into their plug-in unit that changes 120 V or 240 V AC into whatever voltage the device uses. Figure 20.30 shows two different transformers. Notice the wire coils that are visible in each device. The purpose of these coils is explained below.

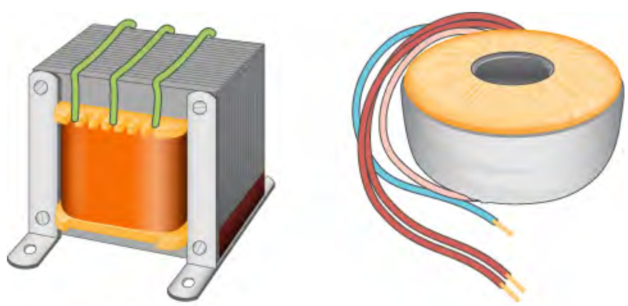


Figure 20.30 On the left is a common laminated-core transformer, which is widely used in electric power transmission and electrical appliances. On the right is a toroidal transformer, which is smaller than the laminated-core transformer for the same power rating but is more expensive to make because of the equipment required to wind the wires in the doughnut shape.

Figure 20.31 shows a laminated-coil transformer, which is based on Faraday's law of induction and is very similar in construction to the apparatus Faraday used to demonstrate that magnetic fields can generate electric currents. The two wire coils are called the primary and secondary coils. In normal use, the input voltage is applied across the primary coil, and the secondary produces the transformed output voltage. Not only does the iron core trap the magnetic field created by the primary coil, but also its magnetization increases the field strength, which is analogous to how a dielectric increases the electric field strength in a capacitor. Since the input voltage is AC, a time-varying magnetic flux is sent through the secondary coil, inducing an AC output voltage.

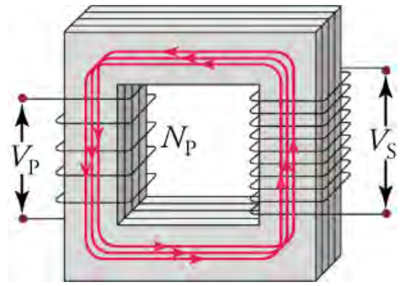


Figure 20.31 A typical construction of a simple transformer has two coils wound on a ferromagnetic core. The magnetic field created by the primary coil is mostly confined to and increased by the core, which transmits it to the secondary coil. Any change in current in the primary coil induces a current in the secondary coil.

LINKS TO PHYSICS

Magnetic Rope Memory

To send men to the moon, the Apollo program had to design an onboard computer system that would be robust, consume little power, and be small enough to fit onboard the spacecraft. In the 1960s, when the Apollo program was launched, entire buildings were regularly dedicated to housing computers whose computing power would be easily outstripped by today's most basic handheld calculator.

To address this problem, engineers at MIT and a major defense contractor turned to *magnetic rope memory*, which was an offshoot of a similar technology used prior to that time for creating random access memories. Unlike random access memory, magnetic rope memory was read-only memory that contained not only data but instructions as well. Thus, it was actually more than memory: It was a hard-wired computer program.

The components of magnetic rope memory were wires and iron rings—which were called *cores*. The iron cores served as transformers, such as that shown in the previous figure. However, instead of looping the wires multiple times around the core, individual wires passed only a single time through the cores, making these single-turn transformers. Up to 63 *word* wires could pass through a single core, along with a single *bit* wire. If a word wire passed through a given core, a voltage pulse on this wire would induce an emf in the bit wire, which would be interpreted as a *one*. If the word wire did not pass through the core, no emf would be induced on the bit wire, which would be interpreted as a *zero*.

Engineers would create programs that would be hard wired into these magnetic rope memories. The wiring process could take as long as a month to complete as workers painstakingly threaded wires through some cores and around others. If any mistakes were made either in the programming or the wiring, debugging would be extraordinarily difficult, if not impossible.

These modules did their job quite well. They are credited with correcting an astronaut mistake in the lunar landing procedure, thereby allowing Apollo 11 to land on the moon. It is doubtful that Michael Faraday ever imagined such an application for magnetic induction when he discovered it.

GRASP CHECK

If the bit wire were looped twice around each core, how would the voltage induced in the bit wire be affected?

a. If number of loops around the wire is doubled, the emf is halved.
b. If number of loops around the wire is doubled, the emf is not affected.
c. If number of loops around the wire is doubled, the emf is also doubled.
d. If number of loops around the wire is doubled, the emf is four times the initial value.

For the transformer shown in Figure 20.31, the output voltage V_S from the secondary coil depends almost entirely on the input voltage V_P across the primary coil and the number of loops in the primary and secondary coils. Faraday's law of induction for the secondary coil gives its induced output voltage V_S to be

$$V_S = -N_S \frac{\Delta \Phi}{\Delta t}, \tag{20.19}$$

where N_S is the number of loops in the secondary coil and $\Delta\Phi/\Delta t$ is the rate of change of magnetic flux. The output voltage equals the induced emf $(V_S = E_S)$, provided coil resistance is small—a reasonable assumption for transformers. The cross-sectional area of the coils is the same on each side, as is the magnetic field strength, and so $\Delta\Phi/\Delta t$ is the same on each side. The input primary voltage V_P is also related to changing flux by

$$V_P = -N_P \frac{\Delta\Phi}{\Delta t}. \tag{20.20}$$

Taking the ratio of these last two equations yields the useful relationship

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}(3.07). \tag{20.21}$$

This is known as the transformer equation. It simply states that the ratio of the secondary voltage to the primary voltage in a transformer equals the ratio of the number of loops in secondary coil to the number of loops in the primary coil.

Transmission of Electrical Power

Transformers are widely used in the electric power industry to increase voltages—called *step-up* transformers—before long-distance transmission via high-voltage wires. They are also used to decrease voltages—called *step-down* transformers—to deliver power to homes and businesses. The overwhelming majority of electric power is generated by using magnetic induction, whereby a wire coil or copper disk is rotated in a magnetic field. The primary energy required to rotate the coils or disk can be provided by a variety of means. Hydroelectric power plants use the kinetic energy of water to drive electric generators. Coal or nuclear power plants create steam to drive steam turbines that turn the coils. Other sources of primary energy include wind, tides, or waves on water.

Once power is generated, it must be transmitted to the consumer, which often means transmitting power over hundreds of kilometers. To do this, the voltage of the power plant is increased by a step-up transformer, that is stepped up, and the current decreases proportionally because

$$P_{\text{transmitted}} = I_{\text{transmitted}} V_{\text{transmitted}}. \tag{20.22}$$

The lower current $I_{\text{transmitted}}$ in the transmission wires reduces the *Joule losses*, which is heating of the wire due to a current flow. This heating is caused by the small, but nonzero, resistance R_{wire} of the transmission wires. The power lost to the environment through this heat is

$$P_{\text{lost}} = I^2_{\text{transmitted}} R_{\text{wire}}, \tag{20.23}$$

which is proportional to the current *squared* in the transmission wire. This is why the transmitted current $I_{\text{transmitted}}$ must be as small as possible and, consequently, the voltage must be large to transmit the power $P_{\text{transmitted}}$.

Voltages ranging from 120 to 700 kV are used for transmitting power over long distances. The voltage is stepped up at the exit of the power station by a step-up transformer, as shown in Figure 20.32.

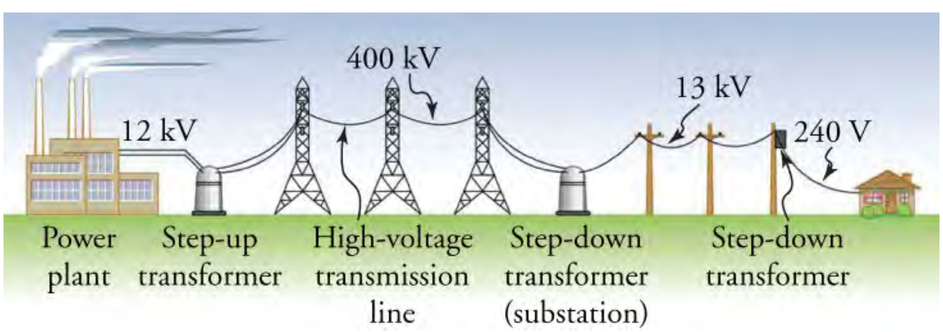


Figure 20.32 Transformers change voltages at several points in a power distribution system. Electric power is usually generated at greater than 10 kV, and transmitted long distances at voltages ranging from 120 kV to 700 kV to limit energy losses. Local power distribution to neighborhoods or industries goes through a substation and is sent short distances at voltages ranging from 5 to 13 kV. This is reduced to 120, 240, or 480 V for safety at the individual user site.

Once the power has arrived at a population or industrial center, the voltage is stepped down at a substation to between 5 and 30 kV. Finally, at individual homes or businesses, the power is stepped down again to 120, 240, or 480 V. Each step-up and step-down transformation is done with a transformer designed based on Faradays law of induction. We've come a long way since Queen Elizabeth asked Faraday what possible use could be made of electricity.

Check Your Understanding

7. What is an electric motor?
   a. An electric motor transforms electrical energy into mechanical energy.
   b. An electric motor transforms mechanical energy into electrical energy.
   c. An electric motor transforms chemical energy into mechanical energy.
   d. An electric motor transforms mechanical energy into chemical energy.

8. What happens to the torque provided by an electric motor if you double the number of coils in the motor?
   a. The torque would be doubled.
   b. The torque would be halved.
   c. The torque would be quadrupled.
   d. The torque would be tripled.

9. What is a step-up transformer?
   a. A step-up transformer decreases the current to transmit power over short distance with minimum loss.
   b. A step-up transformer increases the current to transmit power over short distance with minimum loss.
   c. A step-up transformer increases voltage to transmit power over long distance with minimum loss.
   d. A step-up transformer decreases voltage to transmit power over short distance with minimum loss.

10. What should be the ratio of the number of output coils to the number of input coil in a step-up transformer to increase the voltage fivefold?
   a. The ratio is five times.
   b. The ratio is 10 times.
   c. The ratio is 15 times.
   d. The ratio is 20 times.

20.3 Electromagnetic Induction

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain how a changing magnetic field produces a current in a wire
- Calculate induced electromotive force and current

Section Key Terms

emf   induction   magnetic flux

Changing Magnetic Fields

In the preceding section, we learned that a current creates a magnetic field. If nature is symmetrical, then perhaps a magnetic field can create a current. In 1831, some 12 years after the discovery that an electric current generates a magnetic field, English scientist Michael Faraday (1791–1862) and American scientist Joseph Henry (1797–1878) independently demonstrated that magnetic fields can produce currents. The basic process of generating currents with magnetic fields is called **induction**; this process is also called magnetic induction to distinguish it from charging by induction, which uses the electrostatic Coulomb force.

When Faraday discovered what is now called Faraday's law of induction, Queen Victoria asked him what possible use was electricity. "Madam," he replied, "What good is a baby?" Today, currents induced by magnetic fields are essential to our technological society. The electric generator—found in everything from automobiles to bicycles to nuclear power plants—uses magnetism to generate electric current. Other devices that use magnetism to induce currents include pickup coils in electric guitars, transformers of every size, certain microphones, airport security gates, and damping mechanisms on sensitive chemical balances.

One experiment Faraday did to demonstrate magnetic induction was to move a bar magnet through a wire coil and measure the resulting electric current through the wire. A schematic of this experiment is shown in Figure 20.33. He found that current is induced only when the magnet moves with respect to the coil. When the magnet is motionless with respect to the coil, no current is induced in the coil, as in Figure 20.33. In addition, moving the magnet in the opposite direction (compare Figure 20.33 with Figure 20.33) or reversing the poles of the magnet (compare Figure 20.33 with Figure 20.33) results in a current in the opposite direction.

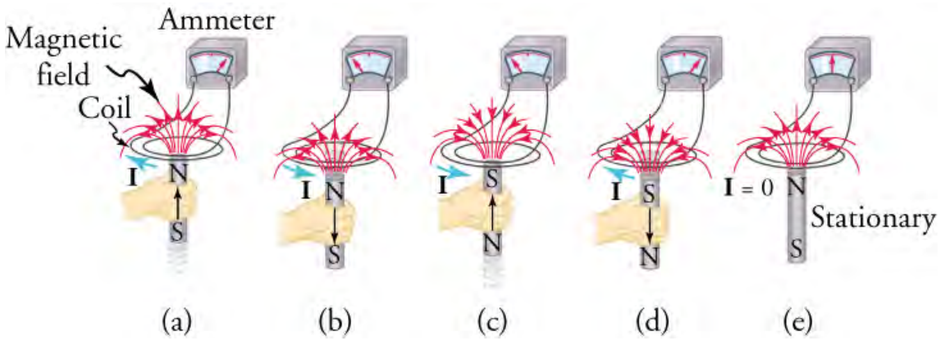


Figure 20.33 Movement of a magnet relative to a coil produces electric currents as shown. The same currents are produced if the coil is moved relative to the magnet. The greater the speed, the greater the magnitude of the current, and the current is zero when there is no motion. The current produced by moving the magnet upward is in the opposite direction as the current produced by moving the magnet downward.

Virtual Physics

Faraday's Law

Click to view content (http://www.openstax.org/l/faradays-law)

Try this simulation to see how moving a magnet creates a current in a circuit. A light bulb lights up to show when current is flowing, and a voltmeter shows the voltage drop across the light bulb. Try moving the magnet through a four-turn coil and through a two-turn coil. For the same magnet speed, which coil produces a higher voltage?

GRASP CHECK

With the north pole to the left and moving the magnet from right to left, a positive voltage is produced as the magnet enters the coil. What sign voltage will be produced if the experiment is repeated with the south pole to the left?

a. The sign of voltage will change because the direction of current flow will change by moving south pole of the magnet to the left.
b. The sign of voltage will remain same because the direction of current flow will not change by moving south pole of the magnet to the left.
c. The sign of voltage will change because the magnitude of current flow will change by moving south pole of the magnet to the left.
d. The sign of voltage will remain same because the magnitude of current flow will not change by moving south pole of the magnet to the left.

Induced Electromotive Force

If a current is induced in the coil, Faraday reasoned that there must be what he called an *electromotive force* pushing the charges through the coil. This interpretation turned out to be incorrect; instead, the external source doing the work of moving the magnet adds energy to the charges in the coil. The energy added per unit charge has units of volts, so the electromotive force is actually a potential. Unfortunately, the name electromotive force stuck and with it the potential for confusing it with a real force. For this reason, we avoid the term *electromotive force* and just use the abbreviation *emf*, which has the mathematical symbol ε. The **emf** may be defined as the rate at which energy is drawn from a source per unit current flowing through a circuit. Thus, emf is the energy per unit charge *added* by a source, which contrasts with voltage, which is the energy per unit charge *released* as the charges flow through a circuit.

To understand why an emf is generated in a coil due to a moving magnet, consider Figure 20.34, which shows a bar magnet moving downward with respect to a wire loop. Initially, seven magnetic field lines are going through the loop (see left-hand image). Because the magnet is moving away from the coil, only five magnetic field lines are going through the loop after a short time Δt (see right-hand image). Thus, when a change occurs in the number of magnetic field lines going through the area defined by the wire loop, an emf is induced in the wire loop. Experiments such as this show that the induced emf is proportional to the *rate of change* of the magnetic field. Mathematically, we express this as

$$\varepsilon \propto \frac{\Delta B}{\Delta t}, \tag{20.24}$$

where ΔB is the change in the magnitude in the magnetic field during time Δt and A is the area of the loop.

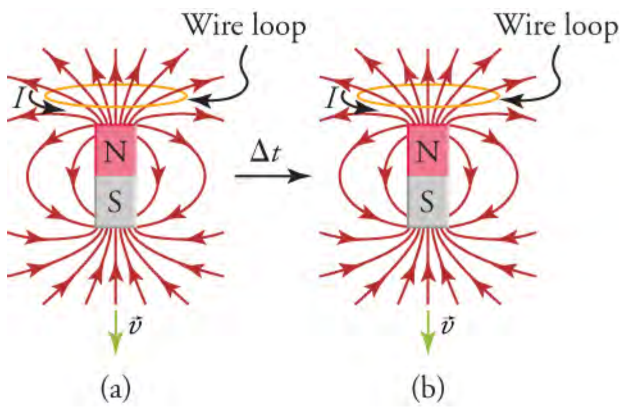


Figure 20.34 The bar magnet moves downward with respect to the wire loop, so that the number of magnetic field lines going through the loop decreases with time. This causes an emf to be induced in the loop, creating an electric current.

Note that magnetic field lines that lie in the plane of the wire loop do not actually pass through the loop, as shown by the left-most loop in Figure 20.35. In this figure, the arrow coming out of the loop is a vector whose magnitude is the area of the loop and whose direction is perpendicular to the plane of the loop. In Figure 20.35, as the loop is rotated from $\theta = 90°$ to $\theta = 0°$, the contribution of the magnetic field lines to the emf increases. Thus, what is important in generating an emf in the wire loop is the component of the magnetic field that is *perpendicular* to the plane of the loop, which is $B\cos\theta$.

This is analogous to a sail in the wind. Think of the conducting loop as the sail and the magnetic field as the wind. To maximize the force of the wind on the sail, the sail is oriented so that its surface vector points in the same direction as the winds, as in the right-most loop in Figure 20.35. When the sail is aligned so that its surface vector is perpendicular to the wind, as in the left-most loop in Figure 20.35, then the wind exerts no force on the sail.

Thus, taking into account the angle of the magnetic field with respect to the area, the proportionality $E \propto \Delta B/\Delta t$ becomes

$$E \propto \frac{\Delta B\cos\theta}{\Delta t}. \tag{20.25}$$

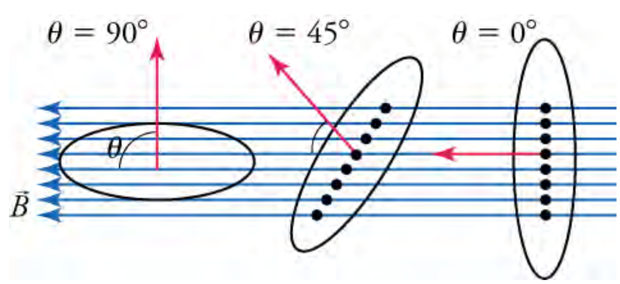


Figure 20.35 The magnetic field lies in the plane of the left-most loop, so it cannot generate an emf in this case. When the loop is rotated so that the angle of the magnetic field with the vector perpendicular to the area of the loop increases to $90°$ (see right-most loop), the magnetic field contributes maximally to the emf in the loop. The dots show where the magnetic field lines intersect the plane defined by the loop.

Another way to reduce the number of magnetic field lines that go through the conducting loop in Figure 20.35 is not to move the magnet but to make the loop smaller. Experiments show that changing the area of a conducting loop in a stable magnetic field induces an emf in the loop. Thus, the emf produced in a conducting loop is proportional to the rate of change of the *product* of the perpendicular magnetic field and the loop area

$$\varepsilon \propto \frac{\Delta\left[(B\cos\theta)A\right]}{\Delta t}, \tag{20.26}$$

where $B\cos\theta$ is the perpendicular magnetic field and A is the area of the loop. The product $BA\cos\theta$ is very important. It is proportional to the number of magnetic field lines that pass perpendicularly through a surface of area A. Going back to our sail analogy, it would be proportional to the force of the wind on the sail. It is called the **magnetic flux** and is represented by Φ .

$$\Phi = BA\cos\theta \tag{20.27}$$

The unit of magnetic flux is the weber (Wb), which is magnetic field per unit area, or T/m^2. The weber is also a volt second (Vs).

The induced emf is in fact proportional to the rate of change of the magnetic flux through a conducting loop.

$$\varepsilon \propto \frac{\Delta\Phi}{\Delta t} \tag{20.28}$$

Finally, for a coil made from N loops, the emf is N times stronger than for a single loop. Thus, the emf induced by a changing magnetic field in a coil of N loops is

$$\varepsilon \propto N\frac{\Delta B\cos\theta}{\Delta t}\text{A}.$$

The last question to answer before we can change the proportionality into an equation is “In what direction does the current flow?” The Russian scientist Heinrich Lenz (1804–1865) explained that the current flows in the direction that creates a magnetic field that tries to keep the flux constant in the loop. For example, consider again Figure 20.34. The motion of the bar magnet causes the number of upward-pointing magnetic field lines that go through the loop to decrease. Therefore, an emf is generated in the loop that drives a current in the direction that creates more upward-pointing magnetic field lines. By using the right-hand rule, we see that this current must flow in the direction shown in the figure. To express the fact that the induced emf acts to counter the change in the magnetic flux through a wire loop, a minus sign is introduced into the proportionality $\varepsilon \propto \Delta\Phi/\Delta t.$, which gives Faraday’s law of induction.

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} \tag{20.29}$$

Lenz’s law is very important. To better understand it, consider Figure 20.36, which shows a magnet moving with respect to a wire coil and the direction of the resulting current in the coil. In the top row, the north pole of the magnet approaches the coil, so the magnetic field lines from the magnet point toward the coil. Thus, the magnetic field $\vec{B}_{\text{mag}} = B_{\text{mag}}\,(\hat{x})$ pointing to the right increases in the coil. According to Lenz’s law, the emf produced in the coil will drive a current in the direction that creates a magnetic field $\vec{B}_{\text{coil}} = B_{\text{coil}}\,(-\hat{x})$ inside the coil pointing to the left. This will counter the increase in magnetic flux pointing to the right. To see which way the current must flow, point your right thumb in the desired direction of the magnetic field $\vec{B}_{\text{coil}}$, and the current will flow in the direction indicated by curling your right fingers. This is shown by the image of the right hand in the top row of Figure 20.36. Thus, the current must flow in the direction shown in Figure 4(a).

In Figure 4(b), the direction in which the magnet moves is reversed. In the coil, the right-pointing magnetic field $\vec{B}_{\text{mag}}$ due to the moving magnet decreases. Lenz’s law says that, to counter this decrease, the emf will drive a current that creates an additional right-pointing magnetic field $\vec{B}_{\text{coil}}$ in the coil. Again, point your right thumb in the desired direction of the magnetic field, and the current will flow in the direction indicate by curling your right fingers (Figure 4(b)).

Finally, in Figure 4(c), the magnet is reversed so that the south pole is nearest the coil. Now the magnetic field $\vec{B}_{\text{mag}}$ points toward the magnet instead of toward the coil. As the magnet approaches the coil, it causes the left-pointing magnetic field in the coil to increase. Lenz’s law tells us that the emf induced in the coil will drive a current in the direction that creates a magnetic field pointing to the right. This will counter the increasing magnetic flux pointing to the left due to the magnet. Using the right-hand rule again, as indicated in the figure, shows that the current must flow in the direction shown in Figure 4(c).

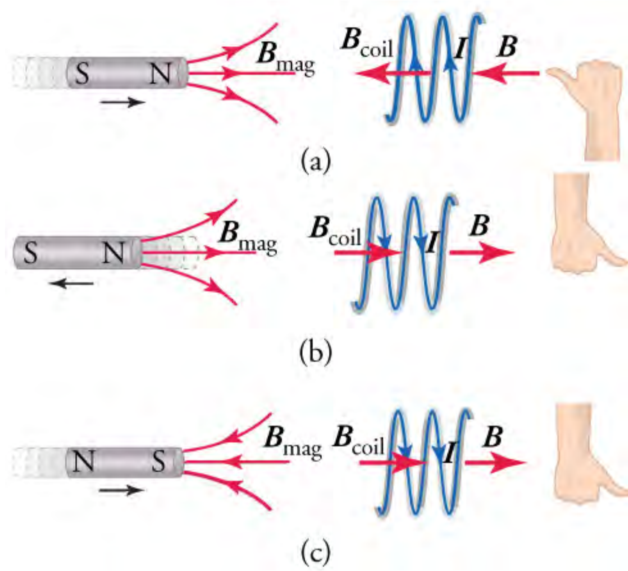


Figure 20.36 Lenz's law tells us that the magnetically induced emf will drive a current that resists the change in the magnetic flux through a circuit. This is shown in panels (a)–(c) for various magnet orientations and velocities. The right hands at right show how to apply the right-hand rule to find in which direction the induced current flows around the coil.

Virtual Physics

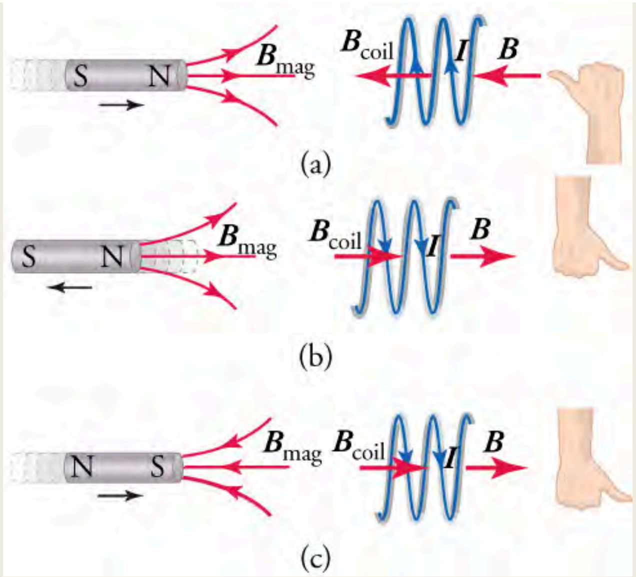
Faraday's Electromagnetic Lab

[Click to view content (http://www.openstax.org/l/Faraday-EM-lab)](http://www.openstax.org/l/Faraday-EM-lab)

This simulation proposes several activities. For now, click on the tab Pickup Coil, which presents a bar magnet that you can move through a coil. As you do so, you can see the electrons move in the coil and a light bulb will light up or a voltmeter will indicate the voltage across a resistor. Note that the voltmeter allows you to see the sign of the voltage as you move the magnet about. You can also leave the bar magnet at rest and move the coil, although it is more difficult to observe the results.

GRASP CHECK

Orient the bar magnet with the north pole facing to the right and place the pickup coil to the right of the bar magnet. Now move the bar magnet toward the coil and observe in which way the electrons move. This is the same situation as depicted below. Does the current in the simulation flow in the same direction as shown below? Explain why or why not.



a. Yes, the current in the simulation flows as shown because the direction of current is opposite to the direction of flow of electrons.
b. No, current in the simulation flows in the opposite direction because the direction of current is same to the direction of flow of electrons.

WATCH PHYSICS

Induced Current in a Wire

This video explains how a current can be induced in a straight wire by moving it through a magnetic field. The lecturer uses the *cross product*, which a type of vector multiplication. Don't worry if you are not familiar with this, it basically combines the right-hand rule for determining the force on the charges in the wire with the equation $F = qvB \sin \theta$.

[Click to view content (https://www.openstax.org/l/induced-current)](https://www.openstax.org/l/induced-current)

GRASP CHECK

What emf is produced across a straight wire 0.50 m long moving at a velocity of (1.5 m/s) $\hat{x}$ through a uniform magnetic field (0.30 T)$\hat{z}$? The wire lies in the $\hat{y}$-direction. Also, which end of the wire is at the higher potential—let the lower end of the wire be at $y = 0$ and the upper end at $y = 0.5$ m)?

a. 0.15 V and the lower end of the wire will be at higher potential
b. 0.15 V and the upper end of the wire will be at higher potential
c. 0.075 V and the lower end of the wire will be at higher potential
d. 0.075 V and the upper end of the wire will be at higher potential

WORKED EXAMPLE

EMF Induced in Conducing Coil by Moving Magnet

Imagine a magnetic field goes through a coil in the direction indicated in Figure 20.37. The coil diameter is 2.0 cm. If the magnetic field goes from 0.020 to 0.010 T in 34 s, what is the direction and magnitude of the induced current? Assume the coil has a resistance of 0.1 Ω.

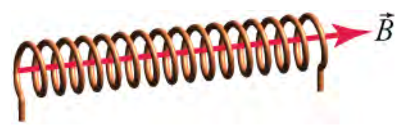


Figure 20.37 A coil through which passes a magnetic field *B*.

STRATEGY

Use the equation $\varepsilon = -N\Delta\Phi/\Delta t$ to find the induced emf in the coil, where $\Delta t = 34\ \text{s}$. Counting the number of loops in the solenoid, we find it has 16 loops, so $N = 16$. Use the equation $\Phi = BA\cos\theta$ to calculate the magnetic flux

$$\Phi = BA\cos\theta = B\pi\left(\frac{d}{2}\right)^2, \tag{20.30}$$

where d is the diameter of the solenoid and we have used $\cos 0° = 1$. Because the area of the solenoid does not vary, the change in the magnetic of the flux through the solenoid is

$$\Delta\Phi = \Delta B\pi\left(\frac{d}{2}\right)^2. \tag{20.31}$$

Once we find the emf, we can use Ohm's law, $\varepsilon = IR$, to find the current.

Finally, Lenz's law tells us that the current should produce a magnetic field that acts to oppose the decrease in the applied magnetic field. Thus, the current should produce a magnetic field to the right.

Solution

Combining equations $\varepsilon = -N\Delta\Phi/\Delta t$ and $\Phi = BA\cos\theta$ gives

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} = -N\frac{\Delta B\pi d^2}{4\ \Delta t}. \tag{20.32}$$

Solving Ohm's law for the current and using this result gives

$$\begin{aligned} I &= \frac{\varepsilon}{R} = -N\frac{\Delta B\pi d^2}{4R\Delta t} \\ &= -16\frac{(-0.010\ \text{T})\pi(0.020\ \text{m})^2}{4(0.10\ \Omega)(34\ \text{s})} \\ &= 15\ \mu\text{A} \end{aligned} \tag{20.33}$$

Lenz's law tells us that the current must produce a magnetic field to the right. Thus, we point our right thumb to the right and curl our right fingers around the solenoid. The current must flow in the direction in which our fingers are pointing, so it enters at the left end of the solenoid and exits at the right end.

Discussion

Let's see if the minus sign makes sense in Faraday's law of induction. Define the direction of the magnetic field to be the positive direction. This means the change in the magnetic field is negative, as we found above. The minus sign in Faraday's law of induction negates the negative change in the magnetic field, leaving us with a positive current. Therefore, the current must flow in the direction of the magnetic field, which is what we found.

Now try defining the positive direction to be the direction opposite that of the magnetic field, that is positive is to the left in Figure 20.37. In this case, you will find a negative current. But since the positive direction is to the left, a negative current must flow to the right, which again agrees with what we found by using Lenz's law.

WORKED EXAMPLE

Magnetic Induction due to Changing Circuit Size

The circuit shown in Figure 20.38 consists of a U-shaped wire with a resistor and with the ends connected by a sliding conducting rod. The magnetic field filling the area enclosed by the circuit is constant at 0.01 T. If the rod is pulled to the right at speed $v = 0.50\ \text{m/s}$, what current is induced in the circuit and in what direction does the current flow?

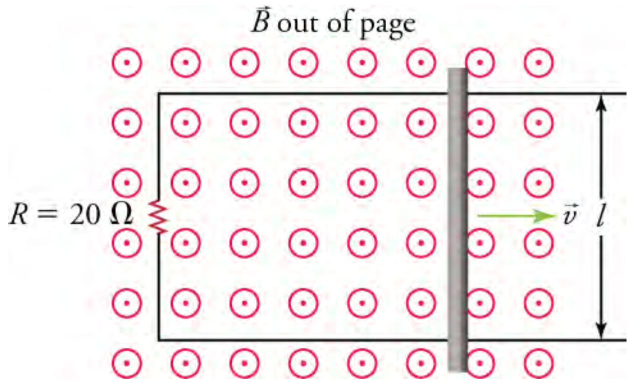


Figure 20.38 A slider circuit. The magnetic field is constant and the rod is pulled to the right at speed *v*. The changing area enclosed by the circuit induces an emf in the circuit.

STRATEGY

We again use Faraday's law of induction, $E = -N\frac{\Delta\Phi}{\Delta t}$, although this time the magnetic field is constant and the area enclosed by the circuit changes. The circuit contains a single loop, so $N = 1$. The rate of change of the area is $\frac{\Delta A}{\Delta t} = v\ell$. Thus the rate of change of the magnetic flux is

$$\frac{\Delta\Phi}{\Delta t} = \frac{\Delta\,(BA\cos\theta)}{\Delta t} = B\frac{\Delta A}{\Delta t} = Bv\ell, \tag{20.34}$$

where we have used the fact that the angle θ between the area vector and the magnetic field is 0°. Once we know the emf, we can find the current by using Ohm's law. To find the direction of the current, we apply Lenz's law.

Solution

Faraday's law of induction gives

$$E = -N\frac{\Delta\Phi}{\Delta t} = -Bv\ell. \tag{20.35}$$

Solving Ohm's law for the current and using the previous result for emf gives

$$I = \frac{E}{R} = \frac{-Bv\ell}{R} = \frac{-\,(0.010\text{ T})\,(0.50\text{ m/s})\,(0.10\text{ m})}{20\ \Omega} = 25\ \mu\text{A}. \tag{20.36}$$

As the rod slides to the right, the magnetic flux passing through the circuit increases. Lenz's law tells us that the current induced will create a magnetic field that will counter this increase. Thus, the magnetic field created by the induced current must be into the page. Curling your right-hand fingers around the loop in the clockwise direction makes your right thumb point into the page, which is the desired direction of the magnetic field. Thus, the current must flow in the clockwise direction around the circuit.

Discussion

Is energy conserved in this circuit? An external agent must pull on the rod with sufficient force to just balance the force on a current-carrying wire in a magnetic field—recall that $F = I\ell B\sin\theta$. The rate at which this force does work on the rod should be balanced by the rate at which the circuit dissipates power. Using $F = I\ell B\sin\theta$, the force required to pull the wire at a constant speed v is

$$F_{\text{pull}} = I\ell B\sin\theta = I\ell B, \tag{20.37}$$

where we used the fact that the angle θ between the current and the magnetic field is $90°$. Inserting our expression above for the current into this equation gives

$$F_{\text{pull}} = I\ell B = -\frac{Bv\ell}{R}(\ell B) = -\frac{B^2v\ell^2}{R}. \tag{20.38}$$

The power contributed by the agent pulling the rod is $F_{\text{pull}}\,v$, or

$$P_{\text{pull}} = F_{\text{pull}} v = -\frac{B^2 v^2 \ell^2}{R}. \tag{20.39}$$

The power dissipated by the circuit is

$$P_{\text{dissipated}} = I^2 R = \left(\frac{-Bv\ell}{R}\right)^2 R = \frac{B^2 v^2 \ell^2}{R}. \tag{20.40}$$

We thus see that $P_{\text{pull}} + P_{\text{dissipated}} = 0$, which means that power is conserved in the system consisting of the circuit and the agent that pulls the rod. Thus, energy is conserved in this system.

Practice Problems

11. The magnetic flux through a single wire loop changes from 3.5 Wb to 1.5 Wb in 2.0 s. What emf is induced in the loop?

a. −2.0 V
b. −1.0 V
c. +1.0 V
d. +2.0 V

12. What is the emf for a 10-turn coil through which the flux changes at 10 Wb/s?

a. −100 V
b. −10 V
c. +10 V
d. +100 V

Check Your Understanding

13. Given a bar magnet, how can you induce an electric current in a wire loop?

a. An electric current is induced if a bar magnet is placed near the wire loop.
b. An electric current is induced if wire loop is wound around the bar magnet.
c. An electric current is induced if a bar magnet is moved through the wire loop.
d. An electric current is induced if a bar magnet is placed in contact with the wire loop.

14. What factors can cause an induced current in a wire loop through which a magnetic field passes?

a. Induced current can be created by changing the size of the wire loop only.
b. Induced current can be created by changing the orientation of the wire loop only.
c. Induced current can be created by changing the strength of the magnetic field only.
d. Induced current can be created by changing the strength of the magnetic field, changing the size of the wire loop, or changing the orientation of the wire loop.

KEY TERMS

Curie temperature well-defined temperature for ferromagnetic materials above which they cannot be magnetized

domain region within a magnetic material in which the magnetic poles of individual atoms are aligned

electric motor device that transforms electrical energy into mechanical energy

electromagnet device that uses electric current to make a magnetic field

electromagnetism study of electric and magnetic phenomena

emf rate at which energy is drawn from a source per unit current flowing through a circuit

ferromagnetic material such as iron, cobalt, nickel, or gadolinium that exhibits strong magnetic effects

generator device that transforms mechanical energy into electrical energy

induction rate at which energy is drawn from a source per unit current flowing through a circuit

magnetic dipole term that describes magnets because they always have two poles: north and south

magnetic field directional lines around a magnetic material that indicates the direction and magnitude of the magnetic force

magnetic flux component of the magnetic field perpendicular to the surface area through which it passes and multiplied by the area

magnetic pole part of a magnet that exerts the strongest force on other magnets or magnetic material

magnetized material that is induced to be magnetic or that is made into a permanent magnet

north pole part of a magnet that orients itself toward the geographic North Pole of Earth

permanent magnet material that retains its magnetic behavior for a long time, even when exposed to demagnetizing influences

right-hand rule rule involving curling the right-hand fingers from one vector to another; the direction in which the right thumb points is the direction of the resulting vector

solenoid uniform cylindrical coil of wire through which electric current is passed to produce a magnetic field

south pole part of a magnet that orients itself toward the geographic South Pole of Earth

transformer device that transforms voltages from one value to another

SECTION SUMMARY

20.1 Magnetic Fields, Field Lines, and Force

- All magnets have two poles: a north pole and a south pole. If the magnet is free to move, its north pole orients itself toward the geographic North Pole of Earth, and the south pole orients itself toward the geographic South Pole of Earth.
- A repulsive force occurs between the north poles of two magnets and likewise for two south poles. However, an attractive force occurs between the north pole of one magnet and the south pole of another magnet.
- A charged particle moving through a magnetic field experiences a force whose direction is determined by the right-hand rule.
- An electric current generates a magnetic field.
- Electromagnets are magnets made by passing a current through a system of wires.

20.2 Motors, Generators, and Transformers

- Electric motors contain wire loops in a magnetic field. Current is passed through the wire loops, which forces them to rotate in the magnetic field. The current is reversed every half rotation so that the torque on the loop is always in the same direction.
- Electric generators contain wire loops in a magnetic field. An external agent provides mechanical energy to force the loops to rotate in the magnetic field, which produces an AC voltage that drives an AC current through the loops.
- Transformers contain a ring made of magnetic material and, on opposite sides of the ring, two windings of wire wrap around the ring. A changing current in one wire winding creates a changing magnetic field, which is trapped in the ring and thus goes through the second winding and induces an emf in the second winding. The voltage in the second winding is proportional to the ratio of the number of loops in each winding.
- Transformers are used to step up and step down the voltage for power transmission.
- Over long distances, electric power is transmitted at high voltage to minimize the current and thereby minimize the Joule losses due to resistive heating.

20.3 Electromagnetic Induction

- **Faraday's law of induction** states that a changing magnetic flux that occurs within an area enclosed by a conducting loop induces an electric current in the loop.
- **Lenz' law** states that an induced current flows in the direction such that it opposes the change that induced it.

KEY EQUATIONS

20.1 Magnetic Fields, Field Lines, and Force

the magnitude of the force on an electric charge	$F = qvB\sin\theta$
the force on a wire carrying current	$F = I\ell B\sin\theta$
the magnitude of the magnetic field created by a long, straight current-carrying wire	$B_{\text{straightwire}} = \frac{\mu_0 I}{2\pi r}$
the magnitude of the magnetic field inside a solenoid	$B_{\text{solenoid}} = \mu_0 \frac{NI}{\ell}$

20.3 Electromagnetic Induction

magnetic flux	$\Phi = BA\cos\theta$
emf	$E = -N\frac{\Delta\Phi}{\Delta t}$

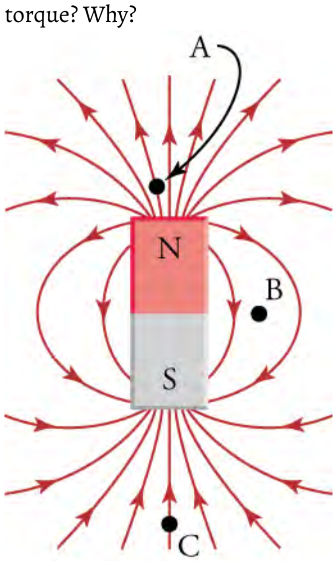
CHAPTER REVIEW

Concept Items

20.1 Magnetic Fields, Field Lines, and Force

1. If you place a small needle between the north poles of two bar magnets, will the needle become magnetized?
    a. Yes, the magnetic fields from the two north poles will point in the same directions.
    b. Yes, the magnetic fields from the two north poles will point in opposite directions.
    c. No, the magnetic fields from the two north poles will point in opposite directions.
    d. No, the magnetic fields from the two north poles will point in the same directions.

2. If you place a compass at the three points in the figure, at which point will the needle experience the greatest torque? Why?



    a. The density of the magnetic field is minimized at B, so the magnetic compass needle will experience the greatest torque at B.
    b. The density of the magnetic field is minimized at C, so the magnetic compass needle will experience the greatest torque at C.
    c. The density of the magnetic field is maximized at B, so the magnetic compass needle will experience the greatest torque at B.
    d. The density of the magnetic field is maximized at A, so the magnetic compass needle will experience the greatest torque at A.

3. In which direction do the magnetic field lines point near the south pole of a magnet?
    a. Outside the magnet the direction of magnetic field lines is towards the south pole of the magnet.
    b. Outside the magnet the direction of magnetic field lines is away from the south pole of the magnet.

20.2 Motors, Generators, and Transformers

4. Consider the angle between the area vector and the magnetic field in an electric motor. At what angles is the torque on the wire loop the greatest?
    a. 0° and 180°
    b. 45° and 135°
    c. 90° and 270°
    d. 225° and 315°

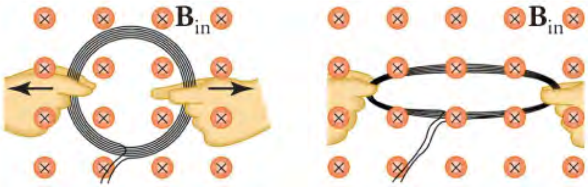
5. What is a voltage transformer?
    a. A transformer is a device that transforms current to voltage.
    b. A transformer is a device that transforms voltages from one value to another.
    c. A transformer is a device that transforms resistance of wire to voltage.

6. Why is electric power transmitted at high voltage?

a. To increase the current for the transmission
b. To reduce energy loss during transmission
c. To increase resistance during transmission
d. To reduce resistance during transmission

20.3 Electromagnetic Induction

7. Yes or no—Is an emf induced in the coil shown when it is stretched? If so, state why and give the direction of the induced current.



a. No, because induced current does not depend upon the area of the coil.
b. Yes, because area of the coil increases; the direction of the induced current is counterclockwise.
c. Yes, because area of the coil increases; the direction of the induced current is clockwise.
d. Yes, because the area of the coil does not change; the direction of the induced current is clockwise.

8. What is Lenz's law?

a. If induced current flows, its direction is such that it adds to the changes which induced it.
b. If induced current flows, its direction is such that it opposes the changes which induced it.
c. If induced current flows, its direction is always clockwise to the changes which induced it.
d. If induced current flows, its direction is always counterclockwise to the changes which induced it.

9. Explain how magnetic flux can be zero when the magnetic field is not zero.

a. If angle between magnetic field and area vector is 0°, then its sine is also zero, which means that there is zero flux.
b. If angle between magnetic field and area vector is 45°, then its sine is also zero, which means that there is zero flux.
c. If angle between magnetic field and area vector is 60°, then its cosine is also zero, which means that there is zero flux.
d. If the angle between magnetic field and area vector is 90°, then its cosine is also zero, which means that there is zero flux.

Critical Thinking Items

20.1 Magnetic Fields, Field Lines, and Force

10. True or false—It is not recommended to place credit cards with magnetic strips near permanent magnets.

a. false
b. true

11. True or false—A square magnet can have sides that alternate between north and south poles.

a. false
b. true

12. You move a compass in a circular plane around a planar magnet. The compass makes four complete revolutions. How many poles does the magnet have?

a. two poles
b. four poles
c. eight poles
d. 12 poles

20.2 Motors, Generators, and Transformers

13. How can you maximize the peak emf from a generator?

a. The peak emf from a generator can be maximized only by maximizing number of turns.
b. The peak emf from a generator can be maximized only by maximizing area of the wired loop.
c. The peak emf from a generator can be maximized only by maximizing frequency.
d. The peak emf from a generator can be maximized by maximizing number of turns, maximizing area of the wired loop or maximizing frequency.

14. Explain why power is transmitted over long distances at high voltages.

a. $P_{lost} = I_{transmitted} V_{transmitted}$, so to maximize current, the voltage must be maximized
b. $P_{transmitted} = I_{transmitted} V_{transmitted}$, so to maximize current, the voltage must be maximized
c. $P_{lost} = I_{transmitted} V_{transmitted}$, so to minimize current, the voltage must be maximized
d. $P_{transmitted} = I_{transmitted} V_{transmitted}$, so to minimize current, the voltage must be maximized

20.3 Electromagnetic Induction

15. To obtain power from the current in the wire of your vacuum cleaner, you place a loop of wire near it to obtain an induced emf. How do you place and orient the loop?

a. A loop of wire should be placed nearest to the vacuum cleaner wire to maximize the magnetic flux through the loop.
b. A loop of wire should be placed farthest to the vacuum cleaner wire to maximize the magnetic flux through the loop.

c. A loop of wire should be placed perpendicular to the vacuum cleaner wire to maximize the magnetic flux through the loop.
d. A loop of wire should be placed at angle greater than 90° to the vacuum cleaner wire to maximize the magnetic flux through the loop.

16. A magneto is a device that creates a spark across a gap by creating a large voltage across the gap. To do this, the device spins a magnet very quickly in front of a wire coil, with the ends of the wires forming the gap. Explain how this creates a sufficiently large voltage to produce a spark.
a. The electric field in the coil increases rapidly due to spinning of magnet which creates an emf in the coil that is proportional to the rate of change of the magnetic flux.
b. The magnetic field in the coil changes rapidly due to spinning of magnet which creates an emf in the coil that is proportional to the rate of change of the magnetic flux.

17. If you drop a copper tube over a bar magnet with its north pole up, is a current induced in the copper tube? If so, in what direction? Consider when the copper tube is approaching the bar magnet.
a. Yes, the induced current will be produced in the clockwise direction when viewed from above.
b. No, the induced current will not be produced.

Problems

20.1 Magnetic Fields, Field Lines, and Force

18. A straight wire segment carries 0.25 A. What length would it need to be to exert a 4.0-mN force on a magnet that produces a uniform magnetic field of 0.015 T that is perpendicular to the wire?
a. 0.55 m
b. 1.10 m
c. 2.20 m
d. 4.40 m

20.3 Electromagnetic Induction

19. What is the current in a wire loop of resistance 10 Ω through which the magnetic flux changes from zero to 10 Wb in 1.0 s?
a. −100 A
b. −2.0 A
c. −1.0 A
d. +1.0 A

20. An emf is induced by rotating a 1,000 turn, 20.0 cm diameter coil in Earth's 5.00×10^{-5} T magnetic field. What average emf is induced, given the plane of the coil is originally perpendicular to Earth's field and is rotated to be parallel to the field in 10.0 ms?
a. -1.6×10^{-4} V
b. $+1.6 \times 10^{-4}$ V
c. $+1.6 \times 10^{-1}$ V
d. -1.6×10^{-1} V

Performance Task

20.2 Motors, Generators, and Transformers

21. Your family takes a trip to Cuba, and rents an old car to drive into the countryside to see the sights. Unfortunately, the next morning you find yourself deep in the countryside and the car won't start because the battery is too weak. Wanting to jump-start the car, you open the hood and find that you can't tell which battery terminal is positive and which is negative. However, you do have a bar magnet with the north and south poles labeled and you manage to find a short wire. How do you use these to determine which terminal is which? For starters, how do you determine the direction of a magnetic field around a current-carrying wire? And in which direction will the force be on another magnet placed in this field? Do you need to worry about the sign of the mobile charge carriers in the wire?

TEST PREP

Multiple Choice

20.1 Magnetic Fields, Field Lines, and Force

22. For a magnet, a domain refers to ______.
a. the region between the poles of the magnet
b. the space around the magnet that is affected by the magnetic field
c. the region within the magnet in which the magnetic poles of individual atoms are aligned
d. the region from which the magnetic material is mined

23. In the region just outside the south pole of a magnet, the magnetic field lines ______.
a. point away from the south pole
b. go around the south pole
c. are less concentrated than at the north pole

d. point toward the south pole

24. Which equation gives the force for a charge moving through a magnetic field?
a. $F = qvB\sin\theta$
b. $F = I\ell B\sin\theta$
c. $F = I\ell B$
d. $F = qvB$

25. Can magnetic field lines cross each other? Explain why or why not.
a. Yes, magnetic field lines can cross each other because that point of intersection indicates two possible directions of magnetic field, which is possible.
b. No, magnetic field lines cannot cross each other because that point of intersection indicates two possible directions of magnetic field, which is not possible.

26. True or false—If a magnet shatters into many small pieces, all the pieces will have north and south poles
a. true
b. false

20.2 Motors, Generators, and Transformers

27. An electrical generator ________.
a. is a generator powered by electricity
b. must be turned by hand
c. converts other sources of power into electrical power
d. uses magnetism to create electrons

28. A step-up transformer increases the
a. voltage from power lines for use in homes
b. current from the power lines for use in homes
c. current from the electrical generator for transmission along power lines
d. voltage from the electrical power plant for transmission along power lines

29. What would be the effect on the torque of an electric motor of doubling the width of the current loop in the motor?
a. Torque remains the same.
b. Torque is doubled.
c. Torque is quadrupled.
d. Torque is halved.

30. Why are the coils of a transformer wrapped around a loop of ferrous material?
a. The magnetic field from the source coil is trapped and also increased in strength.
b. The magnetic field from the source coil is dispersed and also increased in strength.
c. The magnetic field from the source coil is trapped and also decreased in strength.
d. Magnetic field from the source coil is dispersed and also decreased in strength.

20.3 Electromagnetic Induction

31. What does *emf* stand for?
a. electromotive force
b. electro motion force
c. electromagnetic factor
d. electronic magnetic factor

32. Which formula gives magnetic flux?
a. $\frac{\mu_0 I}{2\pi r}$
b. $qvB\sin\ \theta$
c. $-N\frac{\Delta\Phi}{\Delta t}$
d. $BA\cos\theta$

33. What is the relationship between the number of coils in a solenoid and the emf induced in it by a change in the magnetic flux through the solenoid?
a. The induced emf is inversely proportional to the number of coils in a solenoid.
b. The induced emf is directly proportional to the number of coils in a solenoid.
c. The induced emf is inversely proportional to the square of the number of coils in a solenoid.
d. The induced emf is proportional to square of the number of coils in a solenoid.

34. True or false—If you drop a bar magnet through a copper tube, it induces an electric current in the tube.
a. false
b. true

Short Answer

20.1 Magnetic Fields, Field Lines, and Force

35. Given a bar magnet, a needle, a cork, and a bowl full of water, describe how to make a compass.
a. Magnetize the needle by holding it perpendicular to a bar magnet's north pole and pierce the cork along its longitudinal axis by the needle and place the needle-cork combination in the water. The needle now orients itself along the magnetic field lines of Earth.
b. Magnetize the needle by holding it perpendicular to a bar magnet's north pole and pierce the cork along its longitudinal axis by the needle and place the needle-cork combination in the water. The needle now orients itself perpendicular to the

magnetic field lines of Earth.

c. Magnetize the needle by holding its axis parallel to the axis of a bar magnet and pierce the cork along its longitudinal axis by the needle and place the needle-cork combination in the water. The needle now orients itself along the magnetic field lines of Earth.

d. Magnetize the needle by holding its axis parallel to the axis of a bar magnet and pierce the cork along its longitudinal axis by the needle and place the needle-cork combination in the water. The needle now orients itself perpendicular to the magnetic field lines of Earth.

36. Give two differences between electric field lines and magnetic field lines.

a. Electric field lines begin and end on opposite charges and the electric force on a charge is in the direction of field, while magnetic fields form a loop and the magnetic force on a charge is perpendicular to the field.

b. Electric field lines form a loop and the electric force on a charge is in the direction of field, while magnetic fields begin and end on opposite charge and the magnetic force on a charge is perpendicular to the field.

c. Electric field lines begin and end on opposite charges and the electric force on a charge is in the perpendicular direction of field, while magnetic fields form a loop and the magnetic force on a charge is in the direction of the field.

d. Electric field lines form a loop and the electric force on a charge is in the perpendicular direction of field, while magnetic fields begin and end on opposite charge and the magnetic force on a charge is in the direction of the field.

37. To produce a magnetic field of 0.0020 T, what current is required in a 500-turn solenoid that is 25 cm long?

a. 0.80 A

b. 1.60 A

c. 80 A

d. 160 A

38. You magnetize a needle by aligning it along the axis of a bar magnet and just outside the north pole of the magnet. Will the point of the needle that was closest to the bar magnet then be attracted to or repelled from the south pole of another magnet?

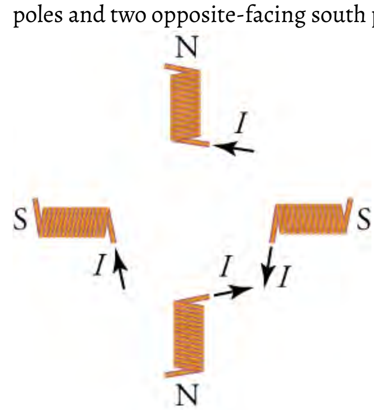
a. The needle will magnetize and the point of needle kept closer to the north pole will act as a south pole. Hence, it will repel the south pole of other magnet.

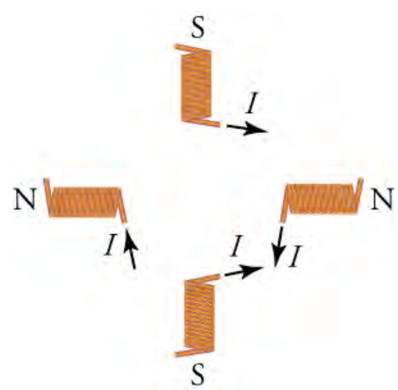
b. The needle will magnetize and the point of needle kept closer to the north pole will act as a south pole. Hence, it will attract the south pole of other magnet.

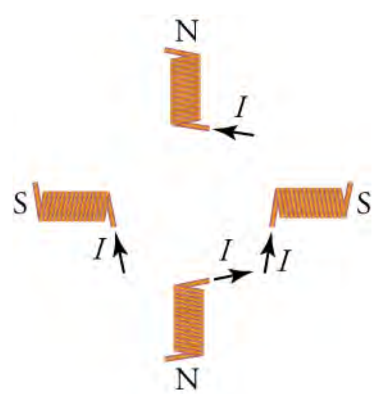
c. The needle will magnetize and the point of a needle kept closer to the north pole will act as a north pole. Hence, it will repel the south pole of the other magnet.

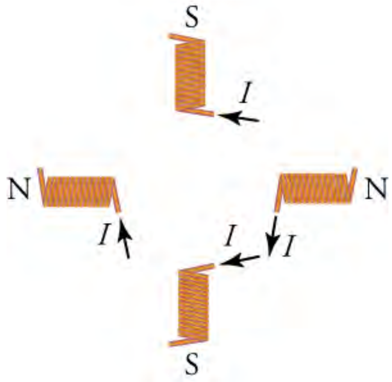
d. The needle will magnetize and the point of needle kept closer to the north pole will act as a north pole. Hence, it will attract the south pole of other magnet.

39. Using four solenoids of the same size, describe how to orient them and in which direction the current should flow to make a magnet with two opposite-facing north poles and two opposite-facing south poles.









40. How far from a straight wire carrying 0.45 A is the magnetic field strength 0.040 T?
   a. 0.23 µm
   b. 0.72 µm
   c. 2.3 µm
   d. 7.2 µm

20.2 Motors, Generators, and Transformers

41. A laminated-coil transformer has a wire coiled 12 times around one of its sides. How many coils should you wrap around the opposite side to get a voltage output that is one half of the input voltage? Explain.
   a. six output coils because the ratio of output to input voltage is the same as the ratio of number of output coils to input coils
   b. 12 output coils because the ratio of output to input voltage is the same as the ratio of number of output coils to input coils
   c. 24 output coils because the ratio of output to input voltage is half the ratio of the number of output coils to input coils
   d. 36 output coils because the ratio of output to input voltage is three times the ratio of the number of output coils to input coils

42. Explain why long-distance electrical power lines are designed to carry very high voltages.
   a. $P_{transmitted} = I_{transmitted>}^2 R_{wire}$ and $P_{lost} = I_{transmitted} V_{transmitted}$, so V must be low to make the current transmitted as high as possible.
   b. $P_{transmitted} = I_{transmitted>}^2 R_{wire}$ and $P_{lost} = I_{lost} V_{lost}$, so V must be low to make the current transmitted as high as possible.
   c. $P_{transmitted} = I_{transmitted>}^2 R_{wire}$ and $P_{lost} = I_{transmitted} V_{transmitted}$, so V must be high to make the current transmitted as low as possible
   d. $P_{lost} = I_{transmitted}^2 R_{wire}$ and $P_{transmitted} = I_{transmitted} V_{transmitted}$, so V must be high to make the current transmitted as low as possible.

43. How is the output emf of a generator affected if you double the frequency of rotation of its coil?
   a. The output emf will be doubled.
   b. The output emf will be halved.
   c. The output emf will be quadrupled.
   d. The output emf will be tripled.

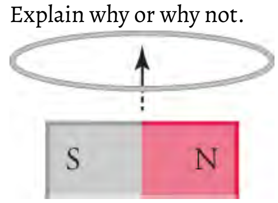
44. In a hydroelectric dam, what is used to power the electrical generators that provide electric power? Explain.
   a. The electric potential energy of stored water is used to produce emf with the help of a turbine.
   b. The electric potential energy of stored water is used to produce resistance with the help of a turbine.
   c. Gravitational potential energy of stored water is used to produce resistance with the help of a turbine.
   d. Gravitational potential energy of stored water is used to produce emf with the help of a turbine.

20.3 Electromagnetic Induction

45. A uniform magnetic field is perpendicular to the plane of a wire loop. If the loop accelerates in the direction of the field, will a current be induced in the loop? Explain why or why not.
   a. No, because magnetic flux through the loop remains constant.
   b. No, because magnetic flux through the loop changes continuously.
   c. Yes, because magnetic flux through the loop remains constant.
   d. Yes, because magnetic flux through the loop changes continuously.

46. The plane of a square wire circuit with side 4.0 cm long is at an angle of 45° with respect to a uniform magnetic field of 0.25 T. The wires have a resistance per unit length of 0.2. If the field drops to zero in 2.5 s, what magnitude current is induced in the square circuit?
   a. 35 µA
   b. 87.5 µA
   c. 3.5 mA
   d. 35 A

47. Yes or no—If a bar magnet moves through a wire loop as shown in the figure, is a current induced in the loop? Explain why or why not.



   a. No, because the net magnetic field passing through the loop is zero.
   b. No, because the net magnetic field passing through

the loop is nonzero.

c. Yes, because the net magnetic field passing through the loop is zero.
d. Yes, because the net magnetic field line passing through the loop is nonzero.

48. What is the magnetic flux through an equilateral triangle with side 60 cm long and whose plane makes a 60° angle with a uniform magnetic field of 0.33 T?

a. 0.045 Wb
b. 0.09 Wb
c. 0.405 Wb
d. 4.5 Wb

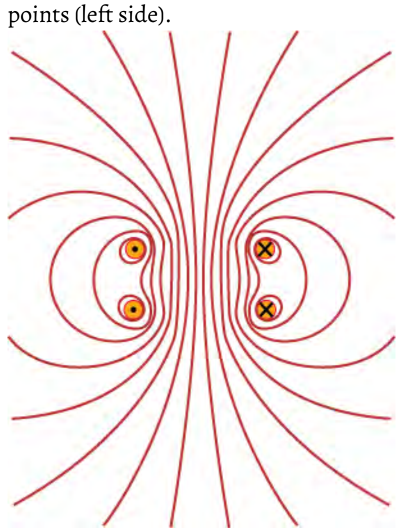
Extended Response

20.1 Magnetic Fields, Field Lines, and Force

49. Summarize the properties of magnets.

a. A magnet can attract metals like iron, nickel, etc., but cannot attract nonmetals like piece of plastic or wood, etc. If free to rotate, an elongated magnet will orient itself so that its north pole will face the magnetic south pole of Earth.
b. A magnet can attract metals like iron, nickel, etc., but cannot attract nonmetals like piece of plastic or wood, etc. If free to rotate, an elongated magnet will orient itself so that its north pole will face the magnetic north pole of Earth.
c. A magnet can attract metals like iron, nickel, etc., and nonmetals like piece of plastic or wood, etc. If free to rotate, an elongated magnet will orient itself so that its north pole will face the magnetic south pole of Earth.
d. A magnet can attract metals like iron, nickel, etc., and nonmetals like piece of plastic or wood, etc. If free to rotate, an elongated magnet will orient itself so that its north pole will face the magnetic north pole of Earth.

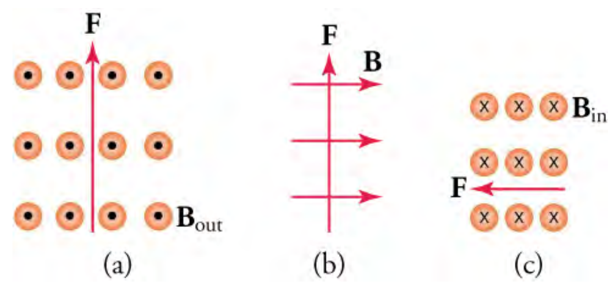
50. The magnetic field shown in the figure is formed by current flowing in two rings that intersect the page at the dots. Current flows into the page at the dots with crosses (right side) and out of the page at the dots with points (left side).



Where is the field strength the greatest and in what direction do the magnetic field lines point?

a. The magnetic field strength is greatest where the magnetic field lines are less dense; magnetic field lines points up the page.
b. The magnetic field strength is greatest where the magnetic field lines are most dense; magnetic field lines points up the page.
c. The magnetic field strength is greatest where the magnetic field lines are most dense; magnetic field lines points down the page.
d. The magnetic field strength is greatest where the magnetic field lines are less dense; magnetic field lines points down the page.

51. The forces shown below are exerted on an electron as it moves through the magnetic field. In each case, what direction does the electron move?



a. (a) left to right, (b) out of the page, (c) upwards
b. (a) left to right, (b) into the page, (c) downwards
c. (a) right to left, (b) out of the page, (c) upwards
d. (a) right to left, (b) into the page, (c) downwards

20.2 Motors, Generators, and Transformers

52. Explain why increasing the frequency of rotation of the coils in an electrical generator increases the output emf.

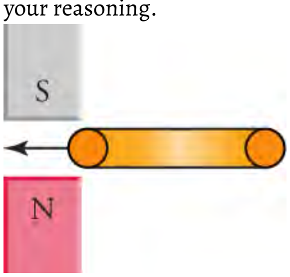
a. The induced emf is proportional to the rate of change of magnetic flux with respect to distance.
b. The induced emf is inversely proportional to the rate of change of magnetic flux with respect to distance.
c. The induced emf is inversely proportional to the rate of change of magnetic flux with respect to time.
d. The induced emf is proportional to the rate of change of magnetic flux with respect to time.

53. Your friend tells you that power lines must carry a maximum current because $P = I^2R$, where R is the resistance of the transmission line. What do you tell her?

a. $P_{transmitted} = I_{transmitted}{}^2 R_{wire}$ and $P_{lost} = I_{transmitted} V_{transmitted}$, so I must be high to reduce power lost due to transmission.
b. $P_{lost} = I_{transmitted}{}^2 R_{wire}$ and $P_{lost} = I_{transmitted} V_{transmitted}$, so I must be high to reduce power lost due to transmission.
c. $P_{transmitted} = I_{transmitted}{}^2 R_{wire}$ and $P_{lost} = I_{transmitted} V_{transmitted}$, so I must be low to reduce power lost due to transmission.
d. $P_{lost} = I_{transmitted}{}^2 R_{wire}$ and $P_{lost} = I_{transmitted} V_{transmitted}$, so I must be low to reduce power lost due to transmission.

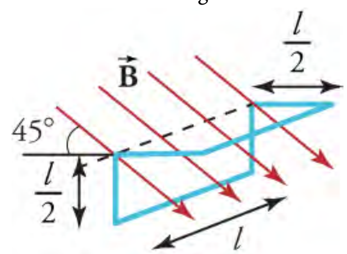
20.3 Electromagnetic Induction

54. When you insert a copper ring between the poles of two bar magnets as shown in the figure, do the magnets exert an attractive or repulsive force on the ring? Explain your reasoning.



a. Magnets exert an attractive force, because magnetic field due to induced current is repulsed by the magnetic field of the magnets.
b. Magnets exert an attractive force, because magnetic field due to induced current is attracted by the magnetic field of the magnets.
c. Magnets exert a repulsive force, because magnetic field due to induced current is repulsed by the magnetic field of the magnets.
d. Magnets exert a repulsive force, because magnetic field due to induced current is attracted by the magnetic field of the magnets.

55. The figure shows a uniform magnetic field passing through a closed wire circuit. The wire circuit rotates at an angular frequency of about the axis shown by the dotted line in the figure.



What is an expression for the magnetic flux through the circuit as a function of time?

a. expression for the magnetic flux through the circuit $\Phi(t) = BA\cos\omega t$
b. expression for the magnetic flux through the circuit $\Phi(t) = \sqrt{2}BA\cos\omega t$
c. expression for the magnetic flux through the circuit $\Phi(t) = \sqrt{3}BA\cos\omega t$
d. expression for the magnetic flux through the circuit $\Phi(t) = 2BA\cos\omega t$

CHAPTER 21
The Quantum Nature of Light

Figure 21.1 In Lewis Carroll's classic text Alice's Adventures in Wonderland, Alice follows a rabbit down a hole into a land of curiosity. While many of her interactions in Wonderland are of surprising consequence, they follow a certain inherent logic. (credit: modification of work by John Tenniel, Wikimedia Commons)

Chapter Outline

21.1 Planck and Quantum Nature of Light

21.2 Einstein and the Photoelectric Effect

21.3 The Dual Nature of Light

INTRODUCTION At first glance, the quantum nature of light can be a strange and bewildering concept. Between light acting as discrete chunks, massless particles providing momenta, and fundamental particles behaving like waves, it may often seem like something out of Alice in Wonderland.

For many, the study of this branch of physics can be as enthralling as Lewis Carroll's classic novel. Recalling the works of legendary characters and brilliant scientists such as Einstein, Planck, and Compton, the study of light's quantum nature will provide you an interesting tale of how a clever interpretation of some small details led to the most important discoveries of the past 150 years. From the electronics revolution of the twentieth century to our future progress in solar energy and space exploration, the quantum nature of light should yield a rabbit hole of curious consequence, within which lie some of the most fascinating truths of our time.

21.1 Planck and Quantum Nature of Light

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe blackbody radiation
- Define quantum states and their relationship to modern physics
- Calculate the quantum energy of lights
- Explain how photon energies vary across divisions of the electromagnetic spectrum

Section Key Terms

blackbody	quantized	quantum	ultraviolet catastrophe

Blackbodies

Our first story of curious significance begins with a T-shirt. You are likely aware that wearing a tight black T-shirt outside on a hot day provides a significantly less comfortable experience than wearing a white shirt. Black shirts, as well as all other black objects, will absorb and re-emit a significantly greater amount of radiation from the sun. This shirt is a good approximation of what is called a **blackbody**.

A perfect blackbody is one that absorbs and re-emits all radiated energy that is incident upon it. Imagine wearing a tight shirt that did this! This phenomenon is often modeled with quite a different scenario. Imagine carving a small hole in an oven that can be heated to very high temperatures. As the temperature of this container gets hotter and hotter, the radiation out of this dark hole would increase as well, re-emitting all energy provided it by the increased temperature. The hole may even begin to glow in different colors as the temperature is increased. Like a burner on your stove, the hole would glow red, then orange, then blue, as the temperature is increased. In time, the hole would continue to glow but the light would be invisible to our eyes. This container is a good model of a perfect blackbody.

It is the analysis of blackbodies that led to one of the most consequential discoveries of the twentieth century. Take a moment to carefully examine Figure 21.2. What relationships exist? What trends can you see? The more time you spend interpreting this figure, the closer you will be to understanding quantum physics!

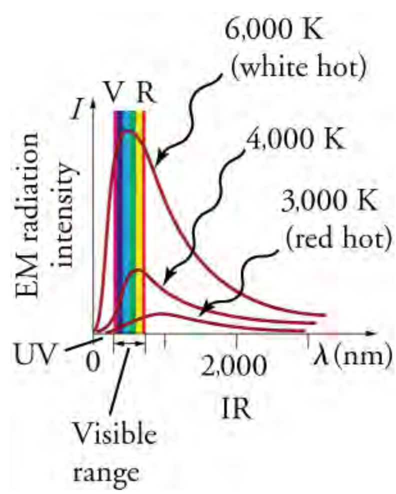


Figure 21.2 Graphs of blackbody radiation (from an ideal radiator) at three different radiator temperatures. The intensity or rate of radiation emission increases dramatically with temperature, and the peak of the spectrum shifts toward the visible and ultraviolet parts of the spectrum. The shape of the spectrum cannot be described with classical physics.

TIPS FOR SUCCESS

When encountering a new graph, it is best to try to interpret the graph before you read about it. Doing this will make the following text more meaningful and will help to remind yourself of some of the key concepts within the section.

Understanding Blackbody Graphs

Figure 21.2 is a plot of radiation intensity against radiated wavelength. In other words, it shows how the intensity of radiated light changes when a blackbody is heated to a particular temperature.

It may help to just follow the bottom-most red line labeled 3,000 K, red hot. The graph shows that when a blackbody acquires a temperature of 3,000 K, it radiates energy across the electromagnetic spectrum. However, the energy is most intensely emitted at a wavelength of approximately 1000 nm. This is in the infrared portion of the electromagnetic spectrum. While a body at this temperature would appear *red-hot* to our eyes, it would truly appear 'infrared-hot' if we were able to see the entire spectrum.

A few other important notes regarding Figure 21.2:

- As temperature increases, the total amount of energy radiated increases. This is shown by examining the area underneath each line.
- Regardless of temperature, all red lines on the graph undergo a consistent pattern. While electromagnetic radiation is emitted throughout the spectrum, the intensity of this radiation peaks at one particular wavelength.
- As the temperature changes, the wavelength of greatest radiation intensity changes. At 4,000 K, the radiation is most intense in the yellow-green portion of the spectrum. At 6,000 K, the blackbody would radiate *white hot,* due to intense radiation throughout the visible portion of the electromagnetic spectrum. Remember that white light is the emission of all visible colors simultaneously.
- As the temperature increases, the frequency of light providing the greatest intensity increases as well. Recall the equation $v = f\lambda$. Because the speed of light is constant, frequency and wavelength are inversely related. This is verified by the leftward movement of the three red lines as temperature is increased.

While in science it is important to categorize observations, theorizing as to why the observations exist is crucial to scientific advancement. Why doesn't a blackbody emit radiation evenly across all wavelengths? Why does the temperature of the body change the peak wavelength that is radiated? Why does an increase in temperature cause the peak wavelength emitted to decrease? It is questions like these that drove significant research at the turn of the twentieth century. And within the context of these questions, Max Planck discovered something of tremendous importance.

Planck's Revolution

The prevailing theory at the time of Max Planck's discovery was that intensity and frequency were related by the equation $I = \frac{2kT}{\lambda^2}$. This equation, derived from classical physics and using wave phenomena, infers that as wavelength increases, the intensity of energy provided will decrease with an inverse-squared relationship. This relationship is graphed in Figure 21.3 and shows a troubling trend. For starters, it should be apparent that the graph from this equation does not match the blackbody graphs found experimentally. Additionally, it shows that for an object of any temperature, there should be an infinite amount of energy quickly emitted in the shortest wavelengths. When theory and experimental results clash, it is important to re-evaluate both models. The disconnect between theory and reality was termed the **ultraviolet catastrophe**.

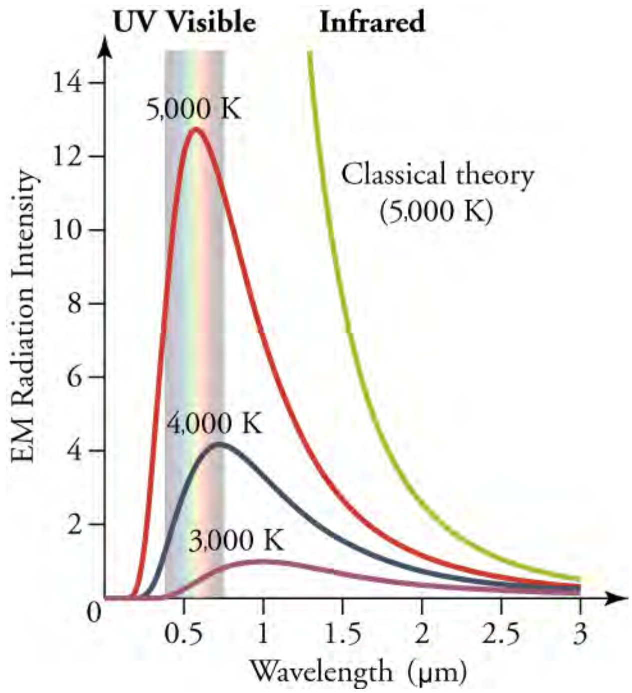


Figure 21.3 The graph above shows the true spectral measurements by a blackbody against those predicted by the classical theory at the time. The discord between the predicted classical theory line and the actual results is known as the ultraviolet catastrophe.

Due to concerns over the ultraviolet catastrophe, Max Planck began to question whether another factor impacted the relationship between intensity and wavelength. This factor, he posited, should affect the probability that short wavelength light would be emitted. Should this factor reduce the probability of short wavelength light, it would cause the radiance curve to not progress infinitely as in the classical theory, but would instead cause the curve to precipitate back downward as is shown in the 5,000 K, 4,000 K, and 3,000 K temperature lines of the graph in Figure 21.3. Planck noted that this factor, whatever it may be, must also be dependent on temperature, as the intensity decreases at lower and lower wavelengths as the temperature increases.

The determination of this *probability factor* was a groundbreaking discovery in physics, yielding insight not just into light but also into energy and matter itself. It would be the basis for Planck's 1918 Nobel Prize in Physics and would result in the transition of physics from classical to modern understanding. In an attempt to determine the cause of the *probability factor,* Max Planck constructed a new theory. This theory, which created the branch of physics called quantum mechanics, speculated that the energy radiated by the blackbody could exist only in specific numerical, or **quantum**, states. This theory is described by the equation $E = nhf$, where *n* is any nonnegative integer (0, 1, 2, 3, …) and *h* is Planck's constant, given by $h = 6.626 \times 10^{-34}\,\text{J}\cdot\text{s}$, and *f* is frequency.

Through this equation, Planck's probability factor can be more clearly understood. Each frequency of light provides a specific quantized amount of energy. Low frequency light, associated with longer wavelengths would provide a smaller amount of energy, while high frequency light, associated with shorter wavelengths, would provide a larger amount of energy. For specified temperatures with specific total energies, it makes sense that more low frequency light would be radiated than high frequency light. To a degree, the relationship is like pouring coins through a funnel. More of the smaller pennies would be able to pass through the funnel than the larger quarters. In other words, because the value of the coin is somewhat related to the size of the coin, the probability of a quarter passing through the funnel is reduced!

Furthermore, an increase in temperature would signify the presence of higher energy. As a result, the greater amount of total blackbody energy would allow for more of the high frequency, short wavelength, energies to be radiated. This permits the peak of the blackbody curve to drift leftward as the temperature increases, as it does from the 3,000 K to 4,000 K to 5,000 K values. Furthering our coin analogy, consider a wider funnel. This funnel would permit more quarters to pass through and allow for a reduction in concern about the *probability factor*.

In summary, it is the interplay between the predicted classical model and the quantum probability that creates the curve depicted in Figure 21.3. Just as quarters have a higher currency denomination than pennies, higher frequencies come with larger amounts of energy. However, just as the probability of a quarter passing through a fixed diameter funnel is reduced, so is the probability of a high frequency light existing in a fixed temperature object. As is often the case in physics, it is the balancing of multiple incredible ideas that finally allows for better understanding.

Quantization

It may be helpful at this point to further consider the idea of quantum states. Atoms, molecules, and fundamental electron and proton charges are all examples of physical entities that are **quantized**—that is, they appear only in certain discrete values and do not have every conceivable value. On the macroscopic scale, this is not a revolutionary concept. A standing wave on a string allows only particular harmonics described by integers. Going up and down a hill using discrete stair steps causes your potential energy to take on discrete values as you move from step to step. Furthermore, we cannot have a fraction of an atom, or part of an electron's charge, or 14.33 cents. Rather, everything is built of integral multiples of these substructures.

That said, to discover quantum states within a phenomenon that science had always considered continuous would certainly be surprising. When Max Planck was able to use quantization to correctly describe the experimentally known shape of the blackbody spectrum, it was the first indication that energy was quantized on a small scale as well. This discovery earned Planck the Nobel Prize in Physics in 1918 and was such a revolutionary departure from classical physics that Planck himself was reluctant to accept his own idea. The general acceptance of Planck's energy quantization was greatly enhanced by Einstein's explanation of the photoelectric effect (discussed in the next section), which took energy quantization a step further.

Figure 21.4 The German physicist Max Planck had a major influence on the early development of quantum mechanics, being the first to recognize that energy is sometimes quantized. Planck also made important contributions to special relativity and classical physics. (credit: Library of Congress, Prints and Photographs Division, Wikimedia Commons)

WORKED EXAMPLE

How Many Photons per Second Does a Typical Light Bulb Produce?

Assuming that 10 percent of a 100-W light bulb's energy output is in the visible range (typical for incandescent bulbs) with an average wavelength of 580 nm, calculate the number of visible photons emitted per second.

Strategy

The number of visible photons per second is directly related to the amount of energy emitted each second, also known as the bulb's power. By determining the bulb's power, the energy emitted each second can be found. Since the power is given in watts, which is joules per second, the energy will be in joules. By comparing this to the amount of energy associated with each photon, the number of photons emitted each second can be determined.

Solution

The power in visible light production is 10.0 percent of 100 W, or 10.0 J/s. The energy of the average visible photon is found by substituting the given average wavelength into the formula

$$E = nhf = \frac{nhc}{\lambda}.$$

By rearranging the above formula to determine energy per photon, this produces

$$E/n = \frac{(6.63 \times 10^{-34}\,\mathrm{J \cdot s})(3.00 \times 10^{8}\,\mathrm{m/s})}{580 \times 10^{-9}\,\mathrm{m}} = 3.43 \times 10^{-19}\,\mathrm{J/photon}. \quad (21.1)$$

The number of visible photons per second is thus

$$\frac{\text{photons}}{\text{sec}} = \frac{10.0\text{J/s}}{3.43 \times 10^{-19}\text{J/photon}} = 2.92 \times 10^{19}\text{photons/s.}$$

Discussion

This incredible number of photons per second is verification that individual photons are insignificant in ordinary human experience. However, it is also a verification of our everyday experience—on the macroscopic scale, photons are so small that quantization becomes essentially continuous.

WORKED EXAMPLE

How does Photon Energy Change with Various Portions of the EM Spectrum?

Refer to the Graphs of Blackbody Radiation shown in the first figure in this section. Compare the energy necessary to radiate one photon of infrared light and one photon of visible light.

Strategy

To determine the energy radiated, it is necessary to use the equation $E = nhf$. It is also necessary to find a representative frequency for infrared light and visible light.

Solution

According to the first figure in this section, one representative wavelength for infrared light is 2000 nm (2.000×10^{-6} m). The associated frequency of an infrared light is

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}\text{m/s}}{2.000 \times 10^{-6}\text{m}} = 1.50 \times 10^{14}\text{Hz.} \quad (21.2)$$

Using the equation $E = nhf$, the energy associated with one photon of representative infrared light is

$$\frac{E}{n} = h \cdot f = \left(6.63 \times 10^{-34}\text{J}\cdot\text{s}\right)\left(1.50 \times 10^{14}\text{Hz}\right) = 9.95 \times 10^{-20}\frac{\text{J}}{\text{photon}}. \quad (21.3)$$

The same process above can be used to determine the energy associated with one photon of representative visible light. According to the first figure in this section, one representative wavelength for visible light is 500 nm.

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}\text{m/s}}{5.00 \times 10^{-7}\text{m}} = 6.00 \times 10^{14}\text{Hz.} \quad (21.4)$$

$$\frac{E}{n} = h \cdot f = \left(6.63 \times 10^{-34}\text{J}\cdot\text{s}\right)\left(6.00 \times 10^{14}\text{Hz}\right) = 3.98 \times 10^{-19}\frac{\text{J}}{\text{photon}}. \quad (21.5)$$

Discussion

This example verifies that as the wavelength of light decreases, the quantum energy increases. This explains why a fire burning with a blue flame is considered more dangerous than a fire with a red flame. Each photon of short-wavelength blue light emitted carries a greater amount of energy than a long-wavelength red light. This example also helps explain the differences in the 3,000 K, 4,000 K, and 6,000 K lines shown in the first figure in this section. As the temperature is increased, more energy is available for a greater number of short-wavelength photons to be emitted.

Practice Problems

1. An AM radio station broadcasts at a frequency of 1,530 kHz . What is the energy in Joules of a photon emitted from this station?
   a. 10.1×10^{-26} J
   b. 1.01×10^{-28} J
   c. 1.01×10^{-29} J
   d. 1.01×10^{-27} J

2. A photon travels with energy of 1.0 eV. What type of EM radiation is this photon?
   a. visible radiation

b. microwave radiation
c. infrared radiation
d. ultraviolet radiation

Check Your Understanding

3. Do reflective or absorptive surfaces more closely model a perfect blackbody?
  a. reflective surfaces
  b. absorptive surfaces

4. A black T-shirt is a good model of a blackbody. However, it is not perfect. What prevents a black T-shirt from being considered a perfect blackbody?
  a. The T-shirt reflects some light.
  b. The T-shirt absorbs all incident light.
  c. The T-shirt re-emits all the incident light.
  d. The T-shirt does not reflect light.

5. What is the mathematical relationship linking the energy of a photon to its frequency?
  a. $E = \frac{hf}{n}$
  b. $E = \frac{nh}{f}$
  c. $E = \frac{nf}{h}$
  d. $E = nhf$

6. Why do we not notice quantization of photons in everyday experience?
  a. because the size of each photon is very large
  b. because the mass of each photon is so small
  c. because the energy provided by photons is very large
  d. because the energy provided by photons is very small

7. Two flames are observed on a stove. One is red while the other is blue. Which flame is hotter?
  a. The red flame is hotter because red light has lower frequency.
  b. The red flame is hotter because red light has higher frequency.
  c. The blue flame is hotter because blue light has lower frequency.
  d. The blue flame is hotter because blue light has higher frequency.

8. Your pupils dilate when visible light intensity is reduced. Does wearing sunglasses that lack UV blockers increase or decrease the UV hazard to your eyes? Explain.
  a. Increase, because more high-energy UV photons can enter the eye.
  b. Increase, because less high-energy UV photons can enter the eye.
  c. Decrease, because more high-energy UV photons can enter the eye.
  d. Decrease, because less high-energy UV photons can enter the eye.

9. The temperature of a blackbody radiator is increased. What will happen to the most intense wavelength of light emitted as this increase occurs?
  a. The wavelength of the most intense radiation will vary randomly.
  b. The wavelength of the most intense radiation will increase.
  c. The wavelength of the most intense radiation will remain unchanged.
  d. The wavelength of the most intense radiation will decrease.

21.2 Einstein and the Photoelectric Effect

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe Einstein's explanation of the photoelectric effect
- Describe how the photoelectric effect could not be explained by classical physics
- Calculate the energy of a photoelectron under given conditions
- Describe use of the photoelectric effect in biological applications, photoelectric devices and movie soundtracks

Section Key Terms

electric eye	photoelectric effect	photoelectron	photon

The Photoelectric Effect

Teacher Support

[EL]Ask the students what they think the term *photoelectric* means. How does the term relate to its definition?

When light strikes certain materials, it can eject electrons from them. This is called the **photoelectric effect**, meaning that light (*photo*) produces electricity. One common use of the photoelectric effect is in light meters, such as those that adjust the automatic iris in various types of cameras. Another use is in solar cells, as you probably have in your calculator or have seen on a rooftop or a roadside sign. These make use of the photoelectric effect to convert light into electricity for running different devices.

Figure 21.5 The photoelectric effect can be observed by allowing light to fall on the metal plate in this evacuated tube. Electrons ejected by the light are collected on the collector wire and measured as a current. A retarding voltage between the collector wire and plate can then be adjusted so as to determine the energy of the ejected electrons. (credit: P. P. Urone)

Revolutionary Properties of the Photoelectric Effect

When Max Planck theorized that energy was quantized in a blackbody radiator, it is unlikely that he would have recognized just how revolutionary his idea was. Using tools similar to the light meter in Figure 21.5, it would take a scientist of Albert Einstein's stature to fully discover the implications of Max Planck's radical concept.

Through careful observations of the photoelectric effect, Albert Einstein realized that there were several characteristics that could be explained only if *EM radiation is itself quantized*. While these characteristics will be explained a bit later in this section, you can already begin to appreciate why Einstein's idea is very important. It means that the apparently continuous stream of energy in an EM wave is actually not a continuous stream at all. In fact, the EM wave itself is actually composed of tiny quantum packets of energy called **photons**.

In equation form, Einstein found the energy of a photon or **photoelectron** to be

$$E = h\mathrm{f},$$

where E is the energy of a photon of frequency f and h is Planck's constant. A beam from a flashlight, which to this point had been considered a wave, instead could now be viewed as a series of photons, each providing a specific amount of energy see Figure 21.6. Furthermore, the amount of energy within each individual photon is based upon its individual frequency, as dictated by $E = hf$. As a result, the total amount of energy provided by the beam could now be viewed as the sum of all frequency-dependent photon energies added together.

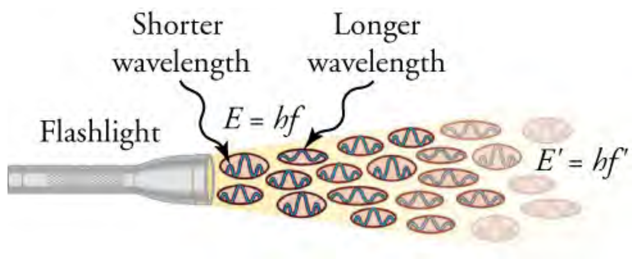


Figure 21.6 An EM wave of frequency *f* is composed of photons, or individual quanta of EM radiation. The energy of each photon is $E = hf$, where *h* is Planck's constant and *f* is the frequency of the EM radiation. Higher intensity means more photons per unit area per second. The flashlight emits large numbers of photons of many different frequencies, hence others have energy $E' = hf'$, and so on.

Just as with Planck's blackbody radiation, Einstein's concept of the photon could take hold in the scientific community only if it could succeed where classical physics failed. The photoelectric effect would be a key to demonstrating Einstein's brilliance.

Consider the following five properties of the photoelectric effect. All of these properties are consistent with the idea that individual photons of EM radiation are absorbed by individual electrons in a material, with the electron gaining the photon's energy. Some of these properties are inconsistent with the idea that EM radiation is a simple wave. For simplicity, let us consider what happens with monochromatic EM radiation in which all photons have the same energy *hf*.

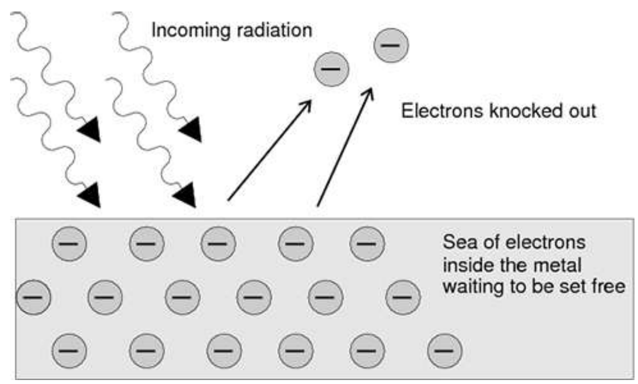


Figure 21.7 Incident radiation strikes a clean metal surface, ejecting multiple electrons from it. The manner in which the frequency and intensity of the incoming radiation affect the ejected electrons strongly suggests that electromagnetic radiation is quantized. This event, called the photoelectric effect, is strong evidence for the existence of photons.

1. If we vary the frequency of the EM radiation falling on a clean metal surface, we find the following: For a given material, there is a threshold frequency f_0 for the EM radiation below which no electrons are ejected, regardless of intensity. Using the photon model, the explanation for this is clear. Individual photons interact with individual electrons. Thus if the energy of an individual photon is too low to break an electron away, no electrons will be ejected. However, if EM radiation were a simple wave, sufficient energy could be obtained simply by increasing the intensity.
2. *Once EM radiation falls on a material, electrons are ejected without delay*. As soon as an individual photon of sufficiently high frequency is absorbed by an individual electron, the electron is ejected. If the EM radiation were a simple wave, several minutes would be required for sufficient energy to be deposited at the metal surface in order to eject an electron.
3. The number of electrons ejected per unit time is proportional to the intensity of the EM radiation and to no other characteristic. High-intensity EM radiation consists of large numbers of photons per unit area, with all photons having the same characteristic energy, *hf*. The increased number of photons per unit area results in an increased number of electrons per unit area ejected.
4. If we vary the intensity of the EM radiation and measure the energy of ejected electrons, we find the following: *The maximum kinetic energy of ejected electrons is independent of the intensity of the EM radiation*. Instead, as noted in point 3 above, increased intensity results in more electrons of the same energy being ejected. If EM radiation were a simple wave, a higher intensity could transfer more energy, and higher-energy electrons would be ejected.
5. The kinetic energy KE of an ejected electron equals the photon energy minus the binding energy BE of the electron in the

specific material. An individual photon can give all of its energy to an electron. The photon's energy is partly used to break the electron away from the material. The remainder goes into the ejected electron's kinetic energy. In equation form, this is given by

$$KE_e = hf - BE, \tag{21.6}$$

where KE_e is the maximum kinetic energy of the ejected electron, hf is the photon's energy, and BE is the binding energy of the electron to the particular material. This equation explains the properties of the photoelectric effect quantitatively and demonstrates that BE is the minimum amount of energy necessary to eject an electron. If the energy supplied is less than BE, the electron cannot be ejected. The binding energy can also be written as $BE = hf_0$, where f_0 is the threshold frequency for the particular material. Figure 21.8 shows a graph of maximum KE_e versus the frequency of incident EM radiation falling on a particular material.

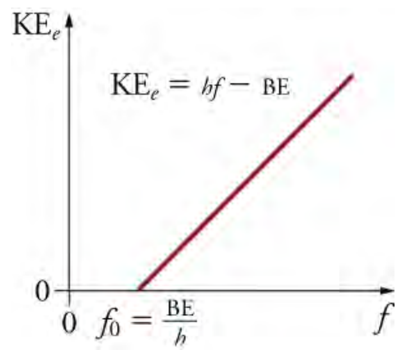


Figure 21.8 A graph of the kinetic energy of an ejected electron, KE$_e$, versus the frequency of EM radiation impinging on a certain material. There is a threshold frequency below which no electrons are ejected, because the individual photon interacting with an individual electron has insufficient energy to break it away. Above the threshold energy, KE$_e$ increases linearly with f, consistent with KE$_e$ = hf − BE. The slope of this line is h, so the data can be used to determine Planck's constant experimentally.

TIPS FOR SUCCESS

The following five pieces of information can be difficult to follow without some organization. It may be useful to create a table of expected results of each of the five properties, with one column showing the classical wave model result and one column showing the modern photon model result.

The table may look something like Table 21.1

	Classical Wave Model	Modern Photon Model
Threshold Frequency		
Electron Ejection Delay		
Intensity of EM Radiation		
Speed of Ejected Electrons		
Relationship between Kinetic Energy and Binding Energy		

Table 21.1 Table of Expected Results

Virtual Physics

Photoelectric Effect

Click to view content (http://www.openstax.org/l/28photoelectric)

In this demonstration, see how light knocks electrons off a metal target, and recreate the experiment that spawned the field of quantum mechanics.

GRASP CHECK

In the circuit provided, what are the three ways to increase the current?

a. decrease the intensity, decrease the frequency, alter the target
b. decrease the intensity, decrease the frequency, don't alter the target
c. increase the intensity, increase the frequency, alter the target
d. increase the intensity, increase the frequency, alter the target

WORKED EXAMPLE

Photon Energy and the Photoelectric Effect: A Violet Light

(a) What is the energy in joules and electron volts of a photon of 420-nm violet light? (b) What is the maximum kinetic energy of electrons ejected from calcium by 420 nm violet light, given that the binding energy of electrons for calcium metal is 2.71 eV?

Strategy

To solve part (a), note that the energy of a photon is given by $E = hf$. For part (b), once the energy of the photon is calculated, it is a straightforward application of $KE_e = hf - BE$ to find the ejected electron's maximum kinetic energy, since BE is given.

Solution for (a)

Photon energy is given by

$$E = hf.$$

Since we are given the wavelength rather than the frequency, we solve the familiar relationship $c = f\lambda$ for the frequency, yielding

$$f = \frac{c}{\lambda} \tag{21.7}$$

Combining these two equations gives the useful relationship

$$E = \frac{hc}{\lambda}. \tag{21.8}$$

Now substituting known values yields

$$E = \frac{\left(6.63 \times 10^{-34} \text{J} \cdot \text{s}\right)\left(3.00 \times 10^{8} m/s\right)}{4.20 \times 10^{-7} m} = 4.74 \times 10^{-19} \text{J}. \tag{21.9}$$

Converting to eV, the energy of the photon is

$$E = (4.74 \times 10^{-19} \text{J} \cdot \text{s}) \frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{J}} = 2.96 \text{ eV}. \tag{21.10}$$

Solution for (b)

Finding the kinetic energy of the ejected electron is now a simple application of the equation $KE_e = hf - BE$. Substituting the photon energy and binding energy yields

$$KE_e = hf - BE = 2.96 \text{ eV} - 2.71 \text{ eV} = 0.25 \text{ eV}. \tag{21.11}$$

Discussion

The energy of this 420 nm photon of violet light is a tiny fraction of a joule, and so it is no wonder that a single photon would be difficult for us to sense directly—humans are more attuned to energies on the order of joules. But looking at the energy in electron volts, we can see that this photon has enough energy to affect atoms and molecules. A DNA molecule can be broken with about 1 eV of energy, for example, and typical atomic and molecular energies are on the order of eV, so that the photon in this example could have biological effects, such as sunburn. The ejected electron has rather low energy, and it would not travel far, except in a vacuum. The electron would be stopped by a retarding potential of only 0.26 eV, a slightly larger KE than calculated above. In fact, if the photon wavelength were longer and its energy less than 2.71 eV, then the formula would give a negative kinetic energy, an impossibility. This simply means that the 420 nm photons with their 2.96 eV energy are not much above the frequency threshold. You can see for yourself that the threshold wavelength is 458 nm (blue light). This means that if calcium metal were used in a light meter, the meter would be insensitive to wavelengths longer than those of blue light. Such a light meter would be completely insensitive to red light, for example.

Practice Problems

10. What is the longest-wavelength EM radiation that can eject a photoelectron from silver, given that the bonding energy is 4.73 eV ? Is this radiation in the visible range?

a. 2.63×10^{-7} m; No, the radiation is in microwave region.
b. 2.63×10^{-7} m; No, the radiation is in visible region.
c. 2.63×10^{-7} m; No, the radiation is in infrared region.
d. 2.63×10^{-7} m; No, the radiation is in ultraviolet region.

11. What is the maximum kinetic energy in eV of electrons ejected from sodium metal by 450-nm EM radiation, given that the binding energy is 2.28 eV?

a. 0.48 V
b. 0.82 eV
c. 1.21 eV
d. 0.48 eV

Technological Applications of the Photoelectric Effect

While Einstein's understanding of the photoelectric effect was a transformative discovery in the early 1900s, its presence is ubiquitous today. If you have watched streetlights turn on automatically in response to the setting sun, stopped elevator doors from closing simply by putting your hands between them, or turned on a water faucet by sliding your hands near it, you are familiar with the **electric eye**, a name given to a group of devices that use the photoelectric effect for detection.

All these devices rely on photoconductive cells. These cells are activated when light is absorbed by a semi-conductive material, knocking off a free electron. When this happens, an electron void is left behind, which attracts a nearby electron. The movement of this electron, and the resultant chain of electron movements, produces a current. If electron ejection continues, further holes are created, thereby increasing the electrical conductivity of the cell. This current can turn switches on and off and activate various familiar mechanisms.

One such mechanism takes place where you may not expect it. Next time you are at the movie theater, pay close attention to the sound coming out of the speakers. This sound is actually created using the photoelectric effect! The audiotape in the projector booth is a transparent piece of film of varying width. This film is fed between a photocell and a bright light produced by an exciter lamp. As the transparent portion of the film varies in width, the amount of light that strikes the photocell varies as well. As a result, the current in the photoconductive circuit changes with the width of the filmstrip. This changing current is converted to a changing frequency, which creates the soundtrack commonly heard in the theater.

WORK IN PHYSICS

Solar Energy Physicist

According to the U.S. Department of Energy, Earth receives enough sunlight each hour to power the entire globe for a year. While converting all of this energy is impossible, the job of the solar energy physicist is to explore and improve upon solar energy conversion technologies so that we may harness more of this abundant resource.

The field of solar energy is not a new one. For over half a century, satellites and spacecraft have utilized photovoltaic cells to create current and power their operations. As time has gone on, scientists have worked to adapt this process so that it may be used in homes, businesses, and full-scale power stations using solar cells like the one shown in Figure 21.9.

Figure 21.9 A solar cell is an example of a photovoltaic cell. As light strikes the cell, the cell absorbs the energy of the photons. If this energy exceeds the binding energy of the electrons, then electrons will be forced to move in the cell, thereby producing a current. This current may be used for a variety of purposes. (credit: U.S. Department of Energy)

Solar energy is converted to electrical energy in one of two manners: direct transfer through photovoltaic cells or thermal conversion through the use of a CSP, concentrating solar power, system. Unlike electric eyes, which trip a mechanism when current is lost, photovoltaic cells utilize semiconductors to directly transfer the electrons released through the photoelectric effect into a directed current. The energy from this current can then be converted for storage, or immediately used in an electric process. A CSP system is an indirect method of energy conversion. In this process, light from the Sun is channeled using parabolic mirrors. The light from these mirrors strikes a thermally conductive material, which then heats a pool of water. This water, in turn, is converted to steam, which turns a turbine and creates electricity. While indirect, this method has long been the traditional means of large-scale power generation.

There are, of course, limitations to the efficacy of solar power. Cloud cover, nightfall, and incident angle strike at high altitudes are all factors that directly influence the amount of light energy available. Additionally, the creation of photovoltaic cells requires rare-earth minerals that can be difficult to obtain. However, the major role of a solar energy physicist is to find ways to improve the efficiency of the solar energy conversion process. Currently, this is done by experimenting with new semi conductive materials, by refining current energy transfer methods, and by determining new ways of incorporating solar structures into the current power grid.

Additionally, many solar physicists are looking into ways to allow for increased solar use in impoverished, more remote locations. Because solar energy conversion does not require a connection to a large-scale power grid, research into thinner, more mobile materials will permit remote cultures to use solar cells to convert sunlight collected during the day into stored energy that can then be used at night.

Regardless of the application, solar energy physicists are an important part of the future in responsible energy growth. While a doctoral degree is often necessary for advanced research applications, a bachelor's or master's degree in a related science or engineering field is typically enough to gain access into the industry. Computer skills are very important for energy modeling, including knowledge of CAD software for design purposes. In addition, the ability to collaborate and communicate with others is critical to becoming a solar energy physicist.

GRASP CHECK

What role does the photoelectric effect play in the research of a solar energy physicist?

a. The understanding of photoelectric effect allows the physicist to understand the generation of light energy when using photovoltaic cells.
b. The understanding of photoelectric effect allows the physicist to understand the generation of electrical energy when using photovoltaic cells.
c. The understanding of photoelectric effect allows the physicist to understand the generation of electromagnetic energy when using photovoltaic cells.
d. The understanding of photoelectric effect allows the physicist to understand the generation of magnetic energy when using photovoltaic cells.

Check Your Understanding

12. How did Einstein's model of photons change the view of a beam of energy leaving a flashlight?
  a. A beam of light energy is now considered a continual stream of wave energy, not photons.
  b. A beam of light energy is now considered a collection of photons, each carrying its own individual energy.

13. True or false—Visible light is the only type of electromagnetic radiation that can cause the photoelectric effect.
  a. false
  b. true

14. Is the photoelectric effect a direct consequence of the wave character of EM radiation or the particle character of EM radiation?
  a. The photoelectric effect is a direct consequence of the particle nature of EM radiation.
  b. The photoelectric effect is a direct consequence of the wave nature of EM radiation.
  c. The photoelectric effect is a direct consequence of both the wave and particle nature of EM radiation.
  d. The photoelectric effect is a direct consequence of neither the wave nor the particle nature of EM radiation.

15. Which aspects of the photoelectric effect can only be explained using photons?
  a. aspects 1, 2, and 3
  b. aspects 1, 2, and 4
  c. aspects 1, 2, 4 and 5
  d. aspects 1, 2, 3, 4 and 5

16. In a photovoltaic cell, what energy transformation takes place?
  a. Solar energy transforms into electric energy.
  b. Solar energy transforms into mechanical energy.
  c. Solar energy transforms into thermal energy.
  d. In a photovoltaic cell, thermal energy transforms into electric energy.

17. True or false—A current is created in a photoconductive cell, even if only one electron is expelled from a photon strike.
  a. false
  b. true

18. What is a photon and how is it different from other fundamental particles?
  a. A photon is a quantum packet of energy; it has infinite mass.
  b. A photon is a quantum packet of energy; it is massless.
  c. A photon is a fundamental particle of an atom; it has infinite mass.
  d. A photon is a fundamental particle of an atom; it is massless.

21.3 The Dual Nature of Light

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe the Compton effect
- Calculate the momentum of a photon
- Explain how photon momentum is used in solar sails
- Explain the particle-wave duality of light

Section Key Terms

Compton effect   particle-wave duality   photon momentum

Photon Momentum

Do photons abide by the fundamental properties of physics? Can packets of electromagnetic energy possibly follow the same rules as a ping-pong ball or an electron? Although strange to consider, the answer to both questions is yes.

Despite the odd nature of photons, scientists prior to Einstein had long suspected that the fundamental particle of electromagnetic radiation shared properties with our more macroscopic particles. This is no clearer than when considering the photoelectric effect, where photons knock electrons out of a substance. While it is strange to think of a massless particle exhibiting momentum, it is now a well-established fact within the scientific community. Figure 21.10 shows macroscopic evidence of **photon momentum**.

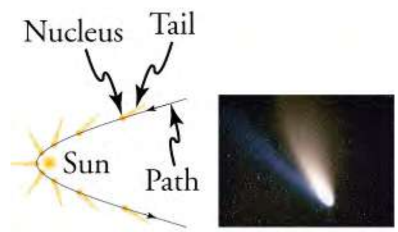


Figure 21.10 The tails of the Hale-Bopp comet point away from the Sun, evidence that light has momentum. Dust emanating from the body of the comet forms this tail. Particles of dust are pushed away from the Sun by light reflecting from them. The blue, ionized gas tail is also produced by photons interacting with atoms in the comet material. (credit: Geoff Chester, U.S. Navy, via Wikimedia Commons)

Figure 21.10 shows a comet with two prominent tails. Comet tails are composed of gases and dust evaporated from the body of the comet and ionized gas. What most people do not know about the tails is that they always point *away* from the Sun rather than trailing behind the comet. This can be seen in the diagram.

Why would this be the case? The evidence indicates that the dust particles of the comet are forced away from the Sun when photons strike them. Evidently, photons carry momentum in the direction of their motion away from the Sun, and some of this momentum is transferred to dust particles in collisions. The blue tail is caused by the solar wind, a stream of plasma consisting primarily of protons and electrons evaporating from the corona of the Sun.

Momentum, The Compton Effect, and Solar Sails

Momentum is conserved in quantum mechanics, just as it is in relativity and classical physics. Some of the earliest direct experimental evidence of this came from the scattering of X-ray photons by electrons in substances, a phenomenon discovered by American physicist Arthur H. Compton (1892–1962). Around 1923, Compton observed that X-rays reflecting from materials had decreased energy and correctly interpreted this as being due to the scattering of the X-ray photons by electrons. This phenomenon could be handled as a collision between two particles—a photon and an electron at rest in the material. After careful observation, it was found that both energy and momentum were conserved in the collision. See Figure 21.11. For the discovery of this conserved scattering, now known as the **Compton effect**, Arthur Compton was awarded the Nobel Prize in 1929.

Shortly after the discovery of Compton scattering, the value of the photon momentum, $\mathbf{p} = \frac{h}{\lambda}$,

was determined by Louis de Broglie. In this equation, called the de Broglie relation, h represents Planck's constant and λ is the photon wavelength.

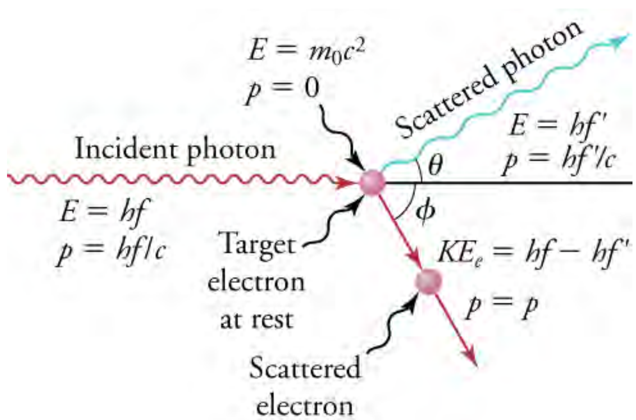


Figure 21.11 The Compton effect is the name given to the scattering of a photon by an electron. Energy and momentum are conserved, resulting in a reduction of both for the scattered photon.

We can see that photon momentum is small, since $\mathbf{p} = h/\lambda$. and h is very small. It is for this reason that we do not ordinarily observe photon momentum. Our mirrors do not recoil when light reflects from them, except perhaps in cartoons. Compton saw the effects of photon momentum because he was observing X-rays, which have a small wavelength and a relatively large momentum, interacting with the lightest of particles, the electron.

WORKED EXAMPLE

Electron and Photon Momentum Compared

(a) Calculate the momentum of a visible photon that has a wavelength of 500 nm. (b) Find the velocity of an electron having the same momentum. (c) What is the energy of the electron, and how does it compare with the energy of the photon?

Strategy

Finding the photon momentum is a straightforward application of its definition: $\mathbf{p} = h/\lambda$. If we find the photon momentum is small, we can assume that an electron with the same momentum will be nonrelativistic, making it easy to find its velocity and kinetic energy from the classical formulas.

Solution for (a)

Photon momentum is given by the de Broglie relation.

$$\mathbf{p} = \frac{h}{\lambda} \tag{21.12}$$

Entering the given photon wavelength yields

$$\mathbf{p} = \frac{6.63 \times 10^{-34} J \cdot s}{5.00 \times 10^{-7} \mathrm{m}} = 1.33 \times 10^{-27} \mathrm{kg \cdot m/s}. \tag{21.13}$$

Solution for (b)

Since this momentum is indeed small, we will use the classical expression $p = mv$ to find the velocity of an electron with this momentum. Solving for v and using the known value for the mass of an electron gives

$$v = \frac{\mathrm{p}}{m} = \frac{1.33 \times 10^{-27} \mathrm{kg \cdot m/s}}{9.11 \times 10^{-31} \mathrm{kg}} = 1{,}459.9 \text{ m/s} \approx 1{,}460 \text{ m/s}. \tag{21.14}$$

Solution for (c)

The electron has kinetic energy, which is classically given by

$$KE_e = \frac{1}{2} m v^2. \tag{21.15}$$

Thus,

$$KE_e = \frac{1}{2}(9.11 \times 10^{-31} \mathrm{kg})(1{,}456 \mathrm{m/s})^2 = 9.64 \times 10^{-25} \mathrm{J}. \tag{21.16}$$

Converting this to eV by multiplying by $\frac{(1 \text{ eV})}{(1.602 \times 10^{-19} \mathrm{J})}$ yields

$$KE_e = 6.02 \times 10^{-6} \mathrm{eV}. \tag{21.17}$$

The photon energy E is

$$E = \frac{hc}{\lambda} = \frac{\left(6.63 \times 10^{-34} \mathrm{J \cdot s}\right)\left(3.00 \times 10^{8} \text{ m/s}\right)}{5.00 \times 10^{-7} \mathrm{m}} = 3.98 \times 10^{-19} \text{ J} = 2.48 \text{ eV}, \tag{21.18}$$

which is about five orders of magnitude greater.

Discussion

Even in huge numbers, the total momentum that photons carry is small. An electron that carries the same momentum as a 500-nm photon will have a 1,460 m/s velocity, which is clearly nonrelativistic. This is borne out by the experimental observation that it takes far less energy to give an electron the same momentum as a photon. That said, for high-energy photons interacting with small masses, photon momentum may be significant. Even on a large scale, photon momentum can have an effect if there are enough of them and if there is nothing to prevent the slow recoil of matter. Comet tails are one example, but there are also proposals to build space sails that use huge low-mass mirrors (made of aluminized Mylar) to reflect sunlight. In the vacuum of space, the mirrors would gradually recoil and could actually accelerate spacecraft within the solar system. See the following figure.

TIPS FOR SUCCESS

When determining energies in particle physics, it is more sensible to use the unit eV instead of Joules. Using eV will help you to recognize differences in magnitude more easily and will make calculations simpler. Also, eV is used by scientists to describe the binding energy of particles and their rest mass, so using eV will eliminate the need to convert energy quantities. Finally, eV is a convenient unit when linking electromagnetic forces to particle physics, as one eV is the amount energy given to an electron when placed in a field of 1-V potential difference.

Practice Problems

19. Find the momentum of a 4.00-cm wavelength microwave photon.

a. 0.83×10^{-32} kg · m/s
b. 1.66×10^{-34} kg · m/s
c. 0.83×10^{-34} kg · m/s
d. 1.66×10^{-32} kg · m/s

20. Calculate the wavelength of a photon that has the same momentum of a proton moving at 1.00 percent of the speed of light.

a. 2.43×10^{-10} m
b. 2.43×10^{-12} m
c. 1.32×10^{-15} m
d. 1.32×10^{-13} m

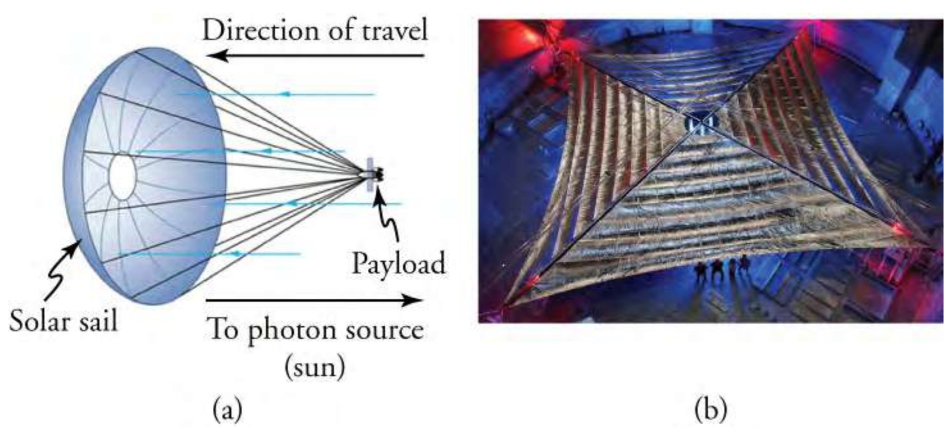


Figure 21.12 (a) Space sails have been proposed that use the momentum of sunlight reflecting from gigantic low-mass sails to propel spacecraft about the solar system. A Russian test model of this (the Cosmos 1) was launched in 2005, but did not make it into orbit due to a rocket failure. (b) A U.S. version of this, labeled LightSail-1, is scheduled for trial launches in 2016. It will have a 40 m2 sail. (credit: Kim Newton/NASA)

LINKS TO PHYSICS

LightSail-1 Project

“Provide ships or sails adapted to the heavenly breezes, and there will be some who will brave even that void.”

— Johannes Kepler (in a letter to Galileo Galilei in 1608)

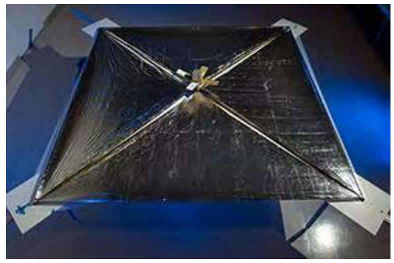


Figure 21.13 NASA's NanoSail-D, a precursor to LightSail-1, with its sails deployed. The Planetary Society will be launching LightSail-1 in early 2016. (credit: NASA/MSFC/D, Wikimedia Commons)

Traversing the Solar System using nothing but the Sun's power has long been a fantasy of scientists and science fiction writers alike. Though physicists like Compton, Einstein, and Planck all provided evidence of light's propulsive capacity, it is only recently that the technology has become available to truly put these visions into motion. In 2016, by sending a lightweight satellite into space, the LightSail-1 project is designed to do just that.

A citizen-funded project headed by the Planetary Society, the 5.45-million-dollar LightSail-1 project is set to launch two crafts into orbit around the Earth. Each craft is equipped with a 32-square-meter solar sail prepared to unfurl once a rocket has launched it to an appropriate altitude. The sails are made of large mirrors, each a quarter of the thickness of a trash bag, which will receive an impulse from the Sun's reflecting photons. Each time the Sun's photon strikes the craft's reflective surface and bounces off, it will provide a momentum to the sail much greater than if the photon were simply absorbed.

Attached to three tiny satellites called CubeSats, whose combined volume is no larger than a loaf of bread, the received momentum from the Sun's photons should be enough to record a substantial increase in orbital speed. The intent of the LightSail-1 mission is to prove that the technology behind photon momentum travel is sound and can be done cheaply. A test flight in May 2015 showed that the craft's Mylar sails could unfurl on command. With another successful result in 2016, the Planetary Society will be planning future versions of the craft with the hopes of eventually achieving interplanetary satellite travel. Though a few centuries premature, Kepler's fantastic vision may not be that far away.

If eventually set into interplanetary launch, what will be the effect of continual photon bombardment on the motion of a craft similar to LightSail-1?

a. It will result in continual acceleration of the craft.
b. It will first accelerate and then decelerate the craft.
c. It will first decelerate and then accelerate the craft.
d. It will result in the craft moving at constant velocity.

Particle-Wave Duality

We have long known that EM radiation is like a wave, capable of interference and diffraction. We now see that light can also be modeled as particles—massless photons of discrete energy and momentum. We call this twofold nature the **particle-wave duality**, meaning that EM radiation has properties of both particles and waves. This may seem contradictory, since we ordinarily deal with large objects that never act like both waves and particles. An ocean wave, for example, looks nothing like a grain of sand. However, this so-called duality is simply a term for properties of the photon analogous to phenomena we can observe directly, on a macroscopic scale. See Figure 21.14. If this term seems strange, it is because we do not ordinarily observe details on the quantum level directly, and our observations yield either particle-like *or* wave-like properties, but never both simultaneously.

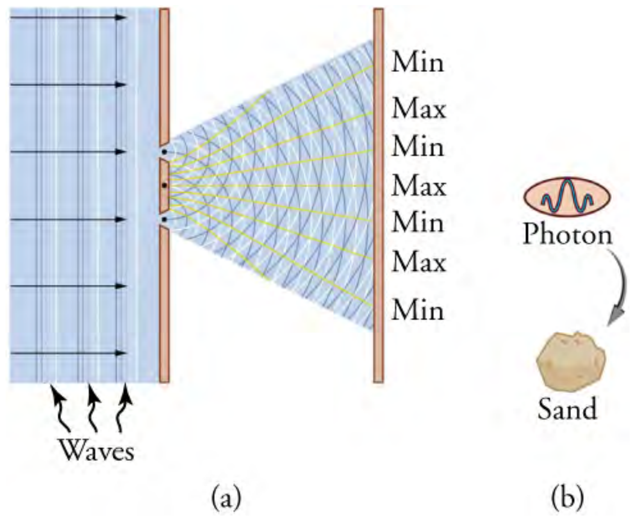


Figure 21.14 (a) The interference pattern for light through a double slit is a wave property understood by analogy to water waves. (b) The properties of photons having quantized energy and momentum and acting as a concentrated unit are understood by analogy to macroscopic particles.

Since we have a particle-wave duality for photons, and since we have seen connections between photons and matter in that both have momentum, it is reasonable to ask whether there is a particle-wave duality for matter as well. If the EM radiation we once thought to be a pure wave has particle properties, is it possible that matter has wave properties? The answer, strangely, is yes. The consequences of this are tremendous, as particle-wave duality has been a constant source of scientific wonder during the twentieth and twenty-first centuries.

Check Your Understanding

21. What fundamental physics properties were found to be conserved in Compton scattering?

a. energy and wavelength
b. energy and momentum
c. mass and energy
d. energy and angle

22. Why do classical or relativistic momentum equations not work in explaining the conservation of momentum that occurs in Compton scattering?

a. because neither classical nor relativistic momentum equations utilize mass as a variable in their equations
b. because relativistic momentum equations utilize mass as a variable in their formulas but classical momentum equations do not
c. because classical momentum equations utilize mass as a variable in their formulas but relativistic momentum equations do not
d. because both classical and relativistic momentum equations utilize mass as a variable in their formulas

23. If solar sails were constructed with more massive materials, how would this influence their effectiveness?

a. The effect of the momentum would increase due to the decreased inertia of the sails.
b. The effect of the momentum would reduce due to the decreased inertia of the sails.
c. The effect of the momentum would increase due to the increased inertia of the sails.
d. The effect of the momentum would be reduced due to the increased inertia of the sails.

24. True or false—It is possible to propel a solar sail craft using just particles within the solar wind.

a. true
b. false

25. True or false—Photon momentum more directly supports the wave model of light.

a. false
b. true

26. True or false—wave-particle duality exists for objects on the macroscopic scale.
   a. false
   b. true

27. What type of electromagnetic radiation was used in Compton scattering?
   a. visible light
   b. ultraviolet radiation
   c. radio waves
   d. X-rays

KEY TERMS

blackbody object that absorbs all radiated energy that strikes it and also emits energy across all wavelengths of the electromagnetic spectrum

Compton effect phenomenon whereby X-rays scattered from materials have decreased energy

electric eye group of devices that use the photoelectric effect for detection

particle-wave duality property of behaving like either a particle or a wave; the term for the phenomenon that all particles have wave-like characteristics and waves have particle-like characteristics

photoelectric effect phenomenon whereby some materials eject electrons when exposed to light

photoelectron electron that has been ejected from a material by a photon of light

photon a quantum, or particle, of electromagnetic radiation

photon momentum amount of momentum of a photon, calculated by $\mathbf{p} = \frac{h}{\lambda}$

quantized the fact that certain physical entities exist only with particular discrete values and not every conceivable value

quantum discrete packet or bundle of a physical entity such as energy

ultraviolet catastrophe misconception that blackbodies would radiate high frequency energy at a much higher rate than energy radiated at lower frequencies

SECTION SUMMARY

21.1 Planck and Quantum Nature of Light

- A blackbody will radiate energy across all wavelengths of the electromagnetic spectrum.
- Radiation of a blackbody will peak at a particular wavelength, dependent on the temperature of the blackbody.
- Analysis of blackbody radiation led to the field of quantum mechanics, which states that radiated energy can only exist in discrete quantum states.

21.2 Einstein and the Photoelectric Effect

- The photoelectric effect is the process in which EM radiation ejects electrons from a material.
- Einstein proposed photons to be quanta of EM radiation having energy $E = hf$, where f is the frequency of the radiation.
- All EM radiation is composed of photons. As Einstein explained, all characteristics of the photoelectric effect are due to the interaction of individual photons with individual electrons.
- The maximum kinetic energy KE_e of ejected electrons (photoelectrons) is given by $KE_e = hf - BE$, where hf is the photon energy and BE is the binding energy (or work function) of the electron in the particular material.

21.3 The Dual Nature of Light

- Compton scattering provided evidence that photon-electron interactions abide by the principles of conservation of momentum and conservation of energy.
- The momentum of individual photons, quantified by $\mathbf{p} = \frac{h}{\lambda}$, can be used to explain observations of comets and may lead to future space technologies.
- Electromagnetic waves and matter have both wave-like and particle-like properties. This phenomenon is defined as particle-wave duality.

KEY EQUATIONS

21.1 Planck and Quantum Nature of Light

quantum energy	$E = nhf$

21.2 Einstein and the Photoelectric Effect

energy of a photon	$E = hf$
maximum kinetic energy of a photoelectron	$KE_e = hf - BE$
binding energy of an electron	$BE = hf_O$

21.3 The Dual Nature of Light

momentum of a photon (deBroglie relation)	$\mathbf{p} = \frac{h}{\lambda}$

CHAPTER REVIEW

Concept Items

21.1 Planck and Quantum Nature of Light

1. What aspect of the blackbody spectrum forced Planck to propose quantization of energy levels in atoms and molecules?
   a. Radiation occurs at a particular frequency that does not change with the energy supplied.
   b. Certain radiation occurs at a particular frequency that changes with the energy supplied.
   c. Maximum radiation would occur at a particular frequency that does not change with the energy supplied.
   d. Maximum radiation would occur at a particular frequency that changes with the energy supplied.

2. Two lasers shine red light at 650 nm. One laser is twice as bright as the other. Explain this difference using photons and photon energy.
   a. The brighter laser emits twice the number of photons and more energy per photon.
   b. The brighter laser emits twice the number of photons and less energy per photon.
   c. Both lasers emit equal numbers of photons and equivalent amounts of energy per photon.
   d. The brighter laser emits twice the number of photons but both lasers emit equivalent amounts of energy per photon.

3. Consider four stars in the night sky: red, yellow, orange, and blue. The photons of which star will carry the greatest amount of energy?
   a. blue
   b. orange
   c. red
   d. yellow

4. A lightbulb is wired to a variable resistor. What will happen to the color spectrum emitted by the bulb as the resistance of the circuit is increased?
   a. The bulb will emit greener light.
   b. The bulb will emit bluer light.
   c. The bulb will emit more ultraviolet light.
   d. The bulb will emit redder light.

21.2 Einstein and the Photoelectric Effect

5. Light is projected onto a semi-conductive surface. However, no electrons are ejected. What will happen when the light intensity is increased?
   a. An increase in light intensity decreases the number of photons. However, no electrons are ejected.
   b. Increase in light intensity increases the number of photons, so electrons with higher kinetic energy are ejected.
   c. An increase in light intensity increases the number of photons, so electrons will be ejected.
   d. An increase in light intensity increases the number of photons. However, no electrons are ejected.

6. True or false—The concept of a work function (or binding energy) is permissible under the classical wave model.
   a. false
   b. true

7. Can a single microwave photon cause cell damage?
   a. No, there is not enough energy associated with a single microwave photon to result in cell damage.
   b. No, there is zero energy associated with a single microwave photon, so it does not result in cell damage.
   c. Yes, a single microwave photon causes cell damage because it does not have high energy.
   d. Yes, a single microwave photon causes cell damage because it has enough energy.

21.3 The Dual Nature of Light

8. Why don't we feel the momentum of sunlight when we are on the beach?
   a. The momentum of a singular photon is incredibly small.
   b. The momentum is not felt because very few photons strike us at any time, and not all have momentum.
   c. The momentum of a singular photon is large, but very few photons strike us at any time.
   d. A large number of photons strike us at any time, and so their combined momentum is incredibly large.

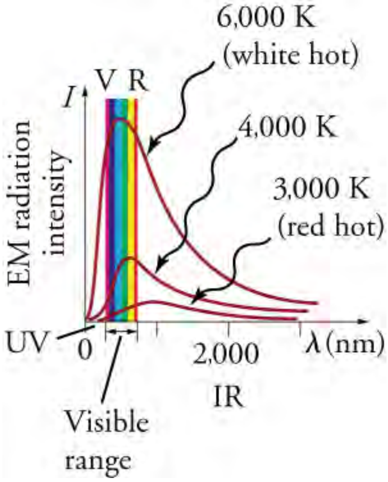
9. If a beam of helium atoms is projected through two slits and onto a screen, will an interference pattern emerge?
   a. No, an interference pattern will not emerge because helium atoms will strike a variety of locations on the screen.
   b. No, an interference pattern will not emerge because helium atoms will strike at certain locations on the screen.
   c. Yes, an interference pattern will emerge because helium atoms will strike a variety of locations on the screen.
   d. Yes, an interference pattern will emerge because helium atoms will strike at certain locations on the screen.

Critical Thinking Items

21.1 Planck and Quantum Nature of Light

10. Explain why the frequency of a blackbody does not double when the temperature is doubled.
   a. Frequency is inversely proportional to temperature.
   b. Frequency is directly proportional to temperature.
   c. Frequency is directly proportional to the square of temperature.
   d. Frequency is directly proportional to the fourth power of temperature.

11. Why does the intensity shown in the blackbody radiation graph decrease after its peak frequency is achieved?



   a. Because after reaching the peak frequency, the photons created at a particular frequency are too many for energy intensity to continue to decrease.
   b. Because after reaching the peak frequency, the photons created at a particular frequency are too few for energy intensity to continue to decrease.
   c. Because after reaching the peak frequency, the photons created at a particular frequency are too many for energy intensity to continue to increase.
   d. Because after reaching the peak frequency, the photons created at a particular frequency are too few for energy intensity to continue to increase.

12. Shortly after the introduction of photography, it was found that photographic emulsions were more sensitive to blue and violet light than they were to red light. Explain why this was the case.
   a. Blue-violet light contains greater amount of energy than red light.
   b. Blue-violet light contains lower amount of energy than red light.
   c. Both blue-violet light and red light have the same frequency but contain different amounts of energy.
   d. Blue-violet light frequency is lower than the frequency of red light.

13. Why is it assumed that a perfect absorber of light (like a blackbody) must also be a perfect emitter of light?
   a. To achieve electrostatic equilibrium with its surroundings
   b. To achieve thermal equilibrium with its surroundings
   c. To achieve mechanical equilibrium with its surroundings
   d. To achieve chemical equilibrium with its surroundings

21.2 Einstein and the Photoelectric Effect

14. Light is projected onto a semi-conductive surface. If the intensity is held constant but the frequency of light is increased, what will happen?
   a. As frequency is increased, electrons will stop being ejected from the surface.
   b. As frequency is increased, electrons will begin to be ejected from the surface.
   c. As frequency is increased, it will have no effect on the electrons being ejected as the intensity is the same.
   d. As frequency is increased, the rate at which the electrons are being ejected will increase.

15. Why is it important to consider what material to use when designing a light meter? Consider the worked example from Section 21-2 for assistance.
   a. A light meter should contain material that responds only to high frequency light.
   b. A light meter should contain material that responds to low frequency light.
   c. A light meter should contain material that has high binding energy.
   d. A light meter should contain a material that does not show any photoelectric effect.

16. Why does overexposure to UV light often result in sunburn when overexposure to visible light does not? This is why you can get burnt even on a cloudy day.
   a. UV light carries less energy than visible light and can penetrate our body.
   b. UV light carries more energy than visible light, so it cannot break bonds at the cellular level.
   c. UV light carries more energy than visible light and can break bonds at the cellular level.
   d. UV light carries less energy than visible light and cannot penetrate the human body.

17. If you pick up and shake a piece of metal that has electrons in it free to move as a current, no electrons fall out. Yet if you heat the metal, electrons can be boiled off. Explain both of these facts as they relate to the amount and distribution of energy involved with shaking the object as compared with heating it.

a. Thermal energy is added to the metal at a much higher rate than energy added due to shaking.
b. Thermal energy is added to the metal at a much lower rate than energy added due to shaking.
c. If the thermal energy added is below the binding energy of the electrons, they may be *boiled off.*
d. If the mechanical energy added is below the binding energy of the electrons, they may be *boiled off.*

21.3 The Dual Nature of Light

18. In many macroscopic collisions, a significant amount of kinetic energy is converted to thermal energy. Explain why this is not a concern for Compton scattering.

a. Because, photons and electrons do not exist on the molecular level, all energy of motion is considered kinetic energy.
b. Because, photons exist on the molecular level while electrons do not exist on the molecular level, all energy of motion is considered kinetic energy.
c. Because, electrons exist on the molecular level while photons do not exist on the molecular level, all energy of motion is considered kinetic energy.
d. Because, photons and electrons exist on the molecular level, all energy of motion is considered kinetic energy.

19. In what region of the electromagnetic spectrum will photons be most effective in accelerating a solar sail?

a. ultraviolet rays
b. infrared rays
c. X-rays
d. gamma rays

20. True or false—Electron microscopes can resolve images that are smaller than the images resolved by light microscopes.

a. false
b. true

21. How would observations of Compton scattering change if ultraviolet light were used in place of X-rays?

a. Ultraviolet light carries less energy than X-rays. As a result, Compton scattering would be easier to detect.
b. Ultraviolet light carries less energy than X-rays. As a result, Compton scattering would be more difficult to detect.
c. Ultraviolet light carries more energy than X-rays. As a result, Compton scattering would be easier to detect.
d. Ultraviolet light has higher energy than X-rays. As a result, Compton scattering would be more difficult to detect.

Problems

21.1 Planck and Quantum Nature of Light

22. How many X-ray photons per second are created by an X-ray tube that produces a flux of X-rays having a power of 1.00 W? Assume the average energy per photon is 75.0 keV.

a. 8.33×10^{15} photons
b. 9.1×10^{7} photons
c. 9.1×10^{8} photons
d. 8.33×10^{13} photons

23. What is the frequency of a photon produced in a CRT using a 25.0-kV accelerating potential? This is similar to the layout as in older color television sets.

a. 6.04×10^{-48} Hz
b. 2.77×10^{-48} Hz
c. 3.02×10^{18} Hz
d. 6.04×10^{18} Hz

21.2 Einstein and the Photoelectric Effect

24. What is the binding energy in eV of electrons in magnesium, if the longest-wavelength photon that can eject electrons is 337 nm?

a. 7.44×10^{-19} J
b. 7.44×10^{-49} J
c. 5.90×10^{-17} J
d. 5.90×10^{-19} J

25. Photoelectrons from a material with a binding energy of 2.71 eV are ejected by 420-nm photons. Once ejected, how long does it take these electrons to travel 2.50 cm to a detection device?

a. 8.5×10^{-6} s
b. 3.5×10^{-7} s
c. 43.5×10^{-9} s
d. 8.5×10^{-8} s

21.3 The Dual Nature of Light

26. What is the momentum of a 0.0100-nm-wavelength photon that could detect details of an atom?

a. 6.626×10^{-27} kg · m/s
b. 6.626×10^{-32} kg · m/s
c. 6.626×10^{-34} kg · m/s
d. 6.626×10^{-23} kg · m/s

27. The momentum of light is exactly reversed when reflected straight back from a mirror, assuming negligible recoil of the mirror. Thus the change in momentum is twice the initial photon momentum. Suppose light of intensity 1.00 kW/m2 reflectsfrom a mirror of area 2.00 m2 each second. Using the most general form of Newton's second law, what is the force on the mirror?

a. 1.33×10^{-5} N
b. 1.33×10^{-6} N
c. 1.33×10^{-7} N
d. 1.33×10^{-8} N

Performance Task

21.3 The Dual Nature of Light

28. Our scientific understanding of light has changed over time. There is evidence to support the wave model of light, just as there is evidence to support the particle model of light.

1. Construct a demonstration that supports the wave model of light. Note—One possible method is to use a piece of aluminum foil, razor blade, and laser to demonstrate wave interference. Can you arrange these materials to create an effective demonstration? In writing, explain how evidence from your demonstration supports the wave model of light.
2. Construct a demonstration that supports the particle model of light. Note—One possible method is to use a negatively charged electroscope, zinc plate, and three light sources of different frequencies. A red laser, a desk lamp, and ultraviolet lamp are typically used. Can you arrange these materials to demonstrate the photoelectric effect? In writing, explain how evidence from your demonstration supports the particle model of light.

TEST PREP

Multiple Choice

21.1 Planck and Quantum Nature of Light

29. A perfect blackbody is a perfect absorber of energy transferred by what method?

a. conduction
b. convection
c. induction
d. radiation

30. Which of the following is a physical entity that is quantized?

a. electric charge of an ion
b. frequency of a sound
c. speed of a car

31. Find the energy in joules of photons of radio waves that leave an FM station that has a 90.0-MHz broadcast frequency.

a. 1.8×10^{-25} J
b. 1.11×10^{-25} J
c. 7.1×10^{-43} J
d. 5.96×10^{-26} J

32. Which region of the electromagnetic spectrum will provide photons of the least energy?

a. infrared light
b. radio waves
c. ultraviolet light
d. X-rays

33. A hot, black coffee mug is sitting on a kitchen table in a dark room. Because it cannot be seen, one assumes that it is not emitting energy in the form of light. Explain the fallacy in this logic.

a. Not all heat is in the form of light energy.
b. Not all light energy falls in the visible portion of the electromagnetic spectrum.
c. All heat is in the form of light energy.
d. All light energy falls in the visible portion of the electromagnetic spectrum.

34. Given two stars of equivalent size, which will have a greater temperature: a red dwarf or a yellow dwarf? Explain. Note—Our sun is considered a yellow dwarf.

a. a yellow dwarf, because yellow light has lower frequency
b. a red dwarf, because red light has lower frequency
c. a red dwarf, because red light has higher frequency
d. a yellow dwarf, because yellow light has higher frequency

21.2 Einstein and the Photoelectric Effect

35. What is a quantum of light called?

a. electron
b. neutron
c. photon
d. proton

36. Which of the following observations from the photoelectric effect is not a violation of classical physics?

a. Electrons are ejected immediately after impact from light.
b. Light can eject electrons from a semi-conductive

material.
c. Light intensity does not influence the kinetic energy of ejected electrons.
d. No electrons are emitted if the light frequency is too low.

37. If $5\ \text{eV}$ of energy is supplied to an electron with a binding energy of $2.3\ \text{eV}$, with what kinetic energy will the electron be launched?
a. $2.3\ \text{eV}$
b. $7.3\ \text{eV}$
c. $11.5\ \text{eV}$
d. $2.7\ \text{eV}$

38. Which of the following terms translates to *light-producing voltage*?
a. photoelectric
b. quantum mechanics
c. photoconductive
d. photovoltaic

39. Why is high frequency EM radiation considered more dangerous than long wavelength EM radiation?
a. Long wavelength EM radiation photons carry less energy and therefore have greater ability to disrupt materials through the photoelectric effect.
b. Long wavelength EM radiation photons carry more energy and therefore have greater ability to disrupt materials through the photoelectric effect.
c. High frequency EM radiation photons carry less energy and therefore have lower ability to disrupt materials through the photoelectric effect.
d. High frequency EM radiation photons carry more energy and therefore have greater ability to disrupt materials through the photoelectric effect.

40. Why are UV, X-rays, and gamma rays considered ionizing radiation?
a. UV, X-rays, and gamma rays are capable of ejecting photons from a surface.
b. UV, X-rays, and gamma rays are capable of ejecting neutrons from a surface.
c. UV, X-rays, and gamma rays are capable of ejecting protons from a surface.
d. UV, X-rays, and gamma rays are capable of ejecting electrons from a surface.

21.3 The Dual Nature of Light

41. What two particles interact in Compton scattering?
a. photon and electron
b. proton and electron
c. neutron and electron
d. proton and neutron

42. What is the momentum of a 500-nm photon?
a. 8.35×10^{-26} kg · m/s
b. 3.31×10^{-40} kg · m/s
c. 7.55×10^{26} kg · m/s
d. 1.33×10^{-27} kg · m/s

43. The conservation of what fundamental physics principle is behind the technology of solar sails?
a. charge
b. mass
c. momentum
d. angular momentum

44. Terms like frequency, amplitude, and period are tied to what component of wave-particle duality?
a. neither the particle nor the wave model of light
b. both the particle and wave models of light
c. the particle model of light
d. the wave model of light

45. Why was it beneficial for Compton to scatter electrons using X-rays and not another region of light like microwaves?
a. because X-rays are more penetrating than microwaves
b. because X-rays have lower frequency than microwaves
c. because microwaves have shorter wavelengths than X-rays
d. because X-rays have shorter wavelength than microwaves

Short Answer

21.1 Planck and Quantum Nature of Light

46. Scientists once assumed that all frequencies of light were emitted with equal probability. Explain what the blackbody radiation curve would look like if this were the case.
a. The blackbody radiation curve would look like a circular path.
b. The blackbody radiation curve would look like an elliptical path.
c. The blackbody radiation curve would look like a vertical line.
d. The blackbody radiation curve would look like a horizontal line.

47. Because there are more gradations to high frequency radiation than low frequency radiation, scientists also thought it possible that a curve titled the *ultraviolet catastrophe* would occur. Explain what the blackbody radiation curve would look like if this were the case.

a. The curve would steadily increase in intensity with increasing frequency.
b. The curve would steadily decrease in intensity with increasing frequency.
c. The curve would be much steeper than in the blackbody radiation graph.
d. The curve would be much flatter than in the blackbody radiation graph.

48. Energy provided by a light exists in the following quantities: 150 J, 225 J, 300 J. Define one possible quantum of energy and provide an energy state that cannot exist with this quantum.
a. 65 J; 450 J cannot exist
b. 70 J; 450 J cannot exist
c. 75 J; 375 J cannot exist
d. 75 J; 100 J cannot exist

49. Why is Planck's recognition of quantum particles considered the dividing line between classical and modern physics?
a. Planck recognized that energy is quantized, which was in sync with the classical physics concepts but not in agreement with modern physics concepts.
b. Planck recognized that energy is quantized, which was in sync with modern physics concepts but not in agreement with classical physics concepts.
c. Prior to Planck's hypothesis, all the classical physics calculations were valid for subatomic particles, but quantum physics calculations were not valid.
d. Prior to Planck's hypothesis, all the classical physics calculations were not valid for macroscopic particles, but quantum physics calculations were valid.

50. How many 500-mm microwave photons are needed to supply the 8 kJ of energy necessary to heat a cup of water by 10 degrees Celsius?
a. 8.05×10^{28} photons
b. 8.05×10^{26} photons
c. 2.01×10^{26} photons
d. 2.01×10^{28} photons

51. What is the efficiency of a 100-W, 550-nm lightbulb if a photometer finds that 1×10^{20} photons are emitted each second?
a. 101 percent
b. 72 percent
c. 18 percent
d. 36 percent

52. Rank the following regions of the electromagnetic spectrum by the amount of energy provided per photon: gamma, infrared, microwave, ultraviolet, radio, visible, X-ray.
a. radio, microwave, infrared, visible, ultraviolet, X-ray, gamma
b. radio, infrared, microwave, ultraviolet, visible, X-ray, gamma
c. radio, visible, microwave, infrared, ultraviolet, X-ray, gamma
d. radio, microwave, infrared, visible, ultraviolet, gamma, X-ray

53. Why are photons of gamma rays and X-rays able to penetrate objects more successfully than ultraviolet radiation?
a. Photons of gamma rays and X-rays carry with them less energy.
b. Photons of gamma rays and X-rays have longer wavelengths.
c. Photons of gamma rays and X-rays have lower frequencies.
d. Photons of gamma rays and X-rays carry with them more energy.

21.2 Einstein and the Photoelectric Effect

54. According to wave theory, what is necessary to eject electrons from a surface?
a. Enough energy to overcome the binding energy of the electrons at the surface
b. A frequency that is higher than that of the electrons at the surface
c. Energy that is lower than the binding energy of the electrons at the surface
d. A very small number of photons

55. What is the wavelength of EM radiation that ejects 2.00-eV electrons from calcium metal, given that the binding energy is 2.71 eV?
a. 16.1×10^{5} m
b. 6.21×10^{-5} m
c. 9.94×10^{-26} m
d. 2.63×10^{-7} m

56. Find the wavelength of photons that eject 0.100-eV electrons from potassium, given that the binding energy is $2.24\,\text{eV}$.
a. 6.22×10^{-7} m
b. 5.92×10^{-5} m
c. 1.24×10^{-5} m
d. 5.31×10^{-7} m

57. How do solar cells utilize the photoelectric effect?
a. A solar cell converts all photons that it absorbs to electrical energy using the photoelectric effect.
b. A solar cell converts all electrons that it absorbs to electrical energy using the photoelectric effect.
c. A solar cell absorbs the photons with energy less

than the energy gap of the material of the solar cell and converts it to electrical energy using the photoelectric effect.
d. A solar cell absorbs the photons with energy greater than the energy gap of the material of the solar cell and converts it to electrical energy using the photoelectric effect.

58. Explain the advantages of the photoelectric effect to other forms of energy transformation.
a. The photoelectric effect is able to work on the Sun's natural energy.
b. The photoelectric effect is able to work on energy generated by burning fossil fuels.
c. The photoelectric effect can convert heat energy into electrical energy.
d. The photoelectric effect can convert electrical energy into light energy.

21.3 The Dual Nature of Light

59. Upon collision, what happens to the frequency of a photon?
a. The frequency of the photon will drop to zero.
b. The frequency of the photon will remain the same.
c. The frequency of the photon will increase.
d. The frequency of the photon will decrease.

60. How does the momentum of a photon compare to the momentum of an electron of identical energy?
a. Momentum of the photon is greater than the momentum of an electron.
b. Momentum of the photon is less than the momentum of an electron.
c. Momentum of the photon is equal to the momentum of an electron.
d. Momentum of the photon is zero due to zero rest mass but the momentum of an electron is finite.

61. A 500-nm photon strikes an electron and loses 20 percent of its energy. What is the new momentum of the photon?
a. 4.24×10^{-27} kg · m/s
b. 3.18×10^{-27} kg · m/s
c. 2.12×10^{-27} kg · m/s
d. 1.06×10^{-27} kg · m/s

62. A 500-nm photon strikes an electron and loses 20 percent of its energy. What is the speed of the recoiling electron?
a. 7.18×10^5 m/s
b. 6.18×10^5 m/s
c. 5.18×10^5 m/s
d. 4.18×10^5 m/s

63. When a photon strikes a solar sail, what is the direction of impulse on the photon?
a. parallel to the sail
b. perpendicular to the sail
c. tangential to the sail
d. opposite to the sail

64. What is a fundamental difference between solar sails and sails that are used on sailboats?
a. Solar sails rely on disorganized strikes from light particles, while sailboats rely on disorganized strikes from air particles.
b. Solar sails rely on disorganized strikes from air particles, while sailboats rely on disorganized strikes from light particles.
c. Solar sails rely on organized strikes from air particles, while sailboats rely on organized strikes from light particles.
d. Solar sails rely on organized strikes from light particles, while sailboats rely on organized strikes from air particles.

65. The wavelength of a particle is called the de Broglie wavelength, and it can be found with the equation $p = \frac{h}{\lambda}$.
Yes or no—Can the wavelength of an electron match that of a proton?
a. Yes, a slow-moving electron can achieve the same momentum as a slow-moving proton.
b. No, a fast-moving electron cannot achieve the same momentum, and hence the same wavelength, as a proton.
c. No, an electron can achieve the same momentum, and hence not the same wavelength, as a proton.
d. Yes, a fast-moving electron can achieve the same momentum, and hence have the same wavelength, as a slow-moving proton.

66. Large objects can move with great momentum. Why then is it difficult to see their wave-like nature?
a. Their wavelength is equal to the object's size.
b. Their wavelength is very small compared to the object's size.
c. Their wavelength is very large compared to the object's size.
d. Their frequency is very small compared to the object's size.

Extended Response

21.1 Planck and Quantum Nature of Light

67. Some television tubes are CRTs. They use an approximately 30-kV accelerating potential to send electrons to the screen, where the electrons stimulate phosphors to emit the light that forms the pictures we watch. Would you expect X-rays also to be created? Explain.
  a. No, because the full spectrum of EM radiation is not emitted at any temperature.
  b. No, because the full spectrum of EM radiation is not emitted at certain temperatures.
  c. Yes, because the full spectrum of EM radiation is emitted at any temperature.
  d. Yes, because the full spectrum of EM radiation is emitted at certain temperatures.

68. If Planck's constant were large, say 10^{34} times greater than it is, we would observe macroscopic entities to be quantized. Describe the motion of a child's swing under such circumstances.
  a. The child would not be able to swing with particular energies.
  b. The child could be released from any height.
  c. The child would be able to swing with constant velocity.
  d. The child could be released only from particular heights.

69. What is the accelerating voltage of an X-ray tube that produces X-rays with the shortest wavelength of 0.0103 nm?
  a. 1.21×10^{10} V
  b. 2.4×10^{5} V
  c. 3.0×10^{-33} V
  d. 1.21×10^{5} V

70. Patients in a doctor's office are rightly concerned about receiving a chest X-ray. Yet visible light is also a form of electromagnetic radiation and they show little concern about sitting under the bright lights of the waiting room. Explain this discrepancy.
  a. X-ray photons carry considerably more energy so they can harm the patients.
  b. X-ray photons carry considerably less energy so they can harm the patients.
  c. X-ray photons have considerably longer wavelengths so they cannot harm the patients.
  d. X-ray photons have considerably lower frequencies so they can harm the patients.

21.2 Einstein and the Photoelectric Effect

71. When increasing the intensity of light shining on a metallic surface, it is possible to increase the current created on that surface. Classical theorists would argue that this is evidence that intensity causes charge to move with a greater kinetic energy. Argue this logic from the perspective of a modern physicist.
  a. The increased intensity increases the number of ejected electrons. The increased current is due to the increase in the number of electrons.
  b. The increased intensity decreases the number of ejected electrons. The increased current is due to the decrease in the number of electrons ejected.
  c. The increased intensity does not alter the number of electrons ejected. The increased current is due to the increase in the kinetic energy of electrons.
  d. The increased intensity alters the number of electrons ejected, but an increase in the current is due to an increase in the kinetic energy of electrons.

72. What impact does the quantum nature of electromagnetic radiation have on the understanding of speed at the particle scale?
  a. Speed must also be quantized at the particle scale.
  b. Speed will not be quantized at the particle scale.
  c. Speed must be zero at the particle scale.
  d. Speed will be infinite at the particle scale.

73. A 500 nm photon of light strikes a semi-conductive surface with a binding energy of 2 eV. With what velocity will an electron be emitted from the semi-conductive surface?
  a. 8.38×10^{5} m/s
  b. 9.33×10^{5} m/s
  c. 3×10^{8} m/s
  d. 4.11×10^{5} m/s

74. True or false—Treating food with ionizing radiation helps keep it from spoiling.
  a. true
  b. false

21.3 The Dual Nature of Light

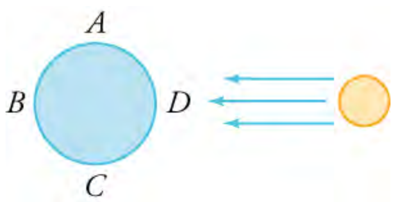
75. When testing atomic bombs, scientists at Los Alamos recognized that huge releases of energy resulted in problems with power and communications systems in the area surrounding the blast site. Explain the possible tie to Compton scattering.
  a. The release of light energy caused large-scale emission of electrons.
  b. The release of light energy caused large-scale emission of protons.
  c. The release of light energy caused large-scale emission of neutrons.
  d. The release of light energy caused large-scale

emission of photons.

76. Sunlight above the Earth's atmosphere has an intensity of 1.30 kW/m2 . If this is reflected straight back from a mirror that has only a small recoil, the light's momentum is exactly reversed, giving the mirror twice the incident momentum. If the mirror were attached to a solar sail craft, how fast would the craft be moving after 24 hr? Note—The average mass per square meter of the craft is 0.100 kg.

a. 8.67×10^{-5} m/s^2
b. 8.67×10^{-6} m/s^2
c. 94.2 m/s
d. 7.49 m/s

77. Consider the counter-clockwise motion of LightSail-1 around Earth. When will the satellite move the fastest?



a. point A
b. point B
c. point C
d. point D

78. What will happen to the interference pattern created by electrons when their velocities are increased?

a. There will be more zones of constructive interference and fewer zones of destructive interference.
b. There will be more zones of destructive interference and fewer zones of constructive interference.
c. There will be more zones of constructive and destructive interference.
d. There will be fewer zones of constructive and destructive interference.

CHAPTER 22
The Atom

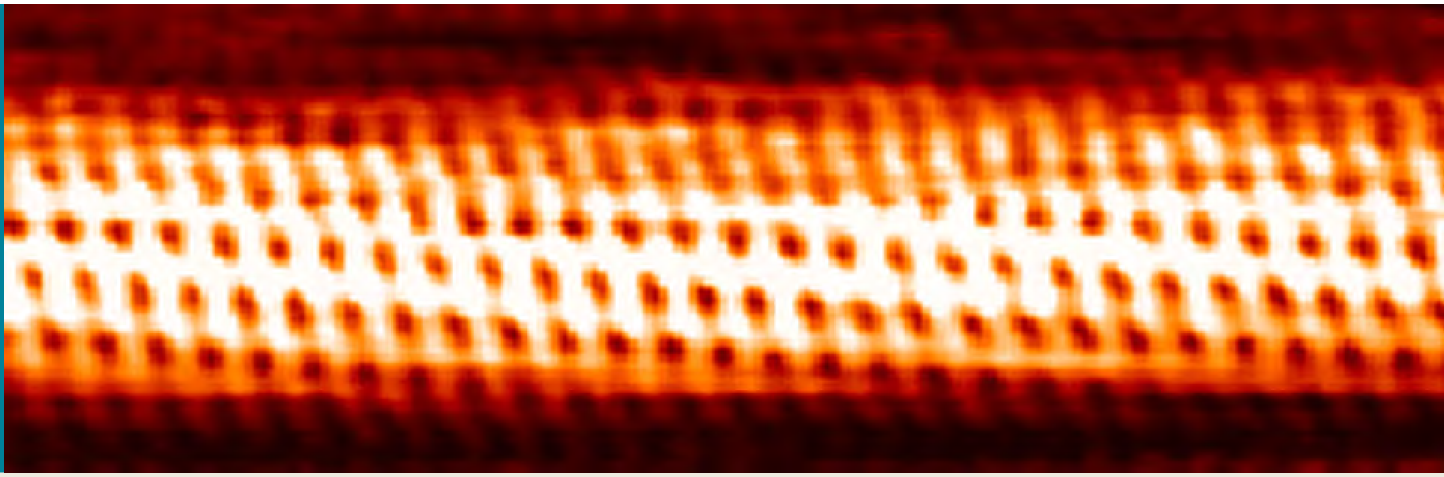


Figure 22.1 Individual carbon atoms are visible in this image of a carbon nanotube made by a scanning tunneling electron microscope. (credit: Taner Yildirim, National Institute of Standards and Technology, Wikimedia Commons)

Chapter Outline

22.1 The Structure of the Atom

22.2 Nuclear Forces and Radioactivity

22.3 Half Life and Radiometric Dating

22.4 Nuclear Fission and Fusion

22.5 Medical Applications of Radioactivity: Diagnostic Imaging and Radiation

INTRODUCTION From childhood on, we learn that atoms are a substructure of all things around us, from the air we breathe to the autumn leaves that blanket a forest trail. Invisible to the eye, the atoms have properties that are used to explain many phenomena—a theme found throughout this text. In this chapter, we discuss the discovery of atoms and their own substructures. We will then learn about the forces that keep them together and the tremendous energy they release when we break them apart. Finally, we will see how the knowledge and manipulation of atoms allows us to better understand geology, biology, and the world around us.

22.1 The Structure of the Atom

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe Rutherford's experiment and his model of the atom
- Describe emission and absorption spectra of atoms
- Describe the Bohr model of the atom
- Calculate the energy of electrons when they change energy levels
- Calculate the frequency and wavelength of emitted photons when electrons change energy levels
- Describe the quantum model of the atom

Section Key Terms

energy-level diagram	excited state	Fraunhofer lines
ground state	Heisenberg Uncertainty Principle	hydrogen-like atoms
planetary model of the atom	Rutherford scattering	Rydberg constant

How do we know that atoms are really there if we cannot see them with our own eyes? While often taken for granted, our knowledge of the existence and structure of atoms is the result of centuries of contemplation and experimentation. The earliest known speculation on the atom dates back to the fifth century B.C., when Greek philosophers Leucippus and Democritus contemplated whether a substance could be divided without limit into ever smaller pieces. Since then, scientists such as John Dalton (1766–1844), Amadeo Avogadro (1776–1856), and Dmitri Mendeleev (1834–1907) helped to discover the properties of that fundamental structure of matter. While much could be written about any number of important scientific philosophers, this section will focus on the role played by Ernest Rutherford (1871–1937). Though his understanding of our most elemental matter is rooted in the success of countless prior investigations, his surprising discovery about the interior of the atom is most fundamental in explaining so many well-known phenomena.

Rutherford's Experiment

In the early 1900's, the *plum pudding* model was the accepted model of the atom. Proposed in 1904 by J. J. Thomson, the model suggested that the atom was a spherical ball of positive charge, with negatively charged electrons scattered evenly throughout. In that model, the positive charges made up the pudding, while the electrons acted as isolated plums. During its short life, the model could be used to explain why most particles were neutral, although with an unbalanced number of plums, electrically charged atoms could exist.

When Ernest Rutherford began his gold foil experiment in 1909, it is unlikely that anyone would have expected that the plum pudding model would be challenged. However, using a radioactive source, a thin sheet of gold foil, and a phosphorescent screen, Rutherford would uncover something so great that he would later call it "the most incredible event that has ever happened to me in my life"[James, L. K. (1993). *Nobel Laureates in Chemistry, 1901–1992*. Washington, DC: American Chemical Society.]

The experiment that Rutherford designed is shown in Figure 22.2. As you can see in, a radioactive source was placed in a lead container with a hole in one side to produce a beam of positively charged helium particles, called *alpha particles*. Then, a thin gold foil sheet was placed in the beam. When the high-energy alpha particles passed through the gold foil, they were scattered. The scattering was observed from the bright spots they produced when they struck the phosphor screen.

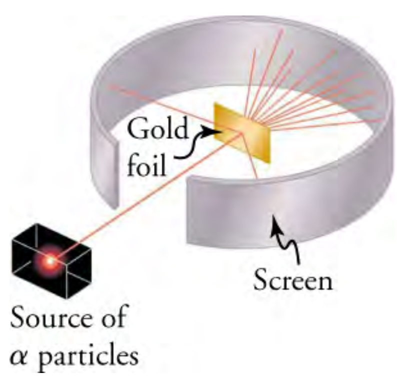


Figure 22.2 Rutherford's experiment gave direct evidence for the size and mass of the nucleus by scattering alpha particles from a thin gold foil. The scattering of particles suggests that the gold nuclei are very small and contain nearly all of the gold atom's mass. Particularly significant in showing the size of the nucleus are alpha particles that scatter to very large angles, much like a soccer ball bouncing off a goalie's head.

The expectation of the plum pudding model was that the high-energy alpha particles would be scattered only slightly by the presence of the gold sheet. Because the energy of the alpha particles was much higher than those typically associated with atoms, the alpha particles should have passed through the thin foil much like a supersonic bowling ball would crash through a few dozen rows of bowling pins. Any deflection was expected to be minor, and due primarily to the electrostatic Coulomb force between the alpha particles and the foil's interior electric charges.

However, the true result was nothing of the sort. While the majority of alpha particles passed through the foil unobstructed, Rutherford and his collaborators Hans Geiger and Ernest Marsden found that alpha particles occasionally were scattered to large angles, and some even came back in the direction from which they came! The result, called **Rutherford scattering**, implied that the gold nuclei were actually very small when compared with the size of the gold atom. As shown in Figure 22.3, the dense nucleus is surrounded by mostly empty space of the atom, an idea verified by the fact that only 1 in 8,000 particles was scattered backward.

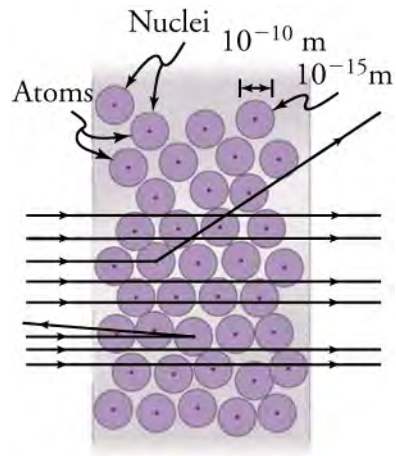


Figure 22.3 An expanded view of the atoms in the gold foil in Rutherford's experiment. Circles represent the atoms that are about 10^{-10} m in diameter, while the dots represent the nuclei that are about 10^{-15} m in diameter. To be visible, the dots are much larger than scale—if the nuclei were actually the size of the dots, each atom would have a diameter of about five meters! Most alpha particles crash through but are relatively unaffected because of their high energy and the electron's small mass. Some, however, strike a nucleus and are scattered straight back. A detailed analysis of their interaction gives the size and mass of the nucleus.

Although the results of the experiment were published by his colleagues in 1909, it took Rutherford two years to convince himself of their meaning. Rutherford later wrote: "It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you. On consideration, I realized that this scattering backwards ... [meant] ... the greatest part of the mass of the atom was concentrated in a tiny nucleus." In 1911, Rutherford published his analysis together with a proposed model of the atom, which was in part based on Geiger's work from the previous year. As a result of the paper, the size of the nucleus was determined to be about 10^{-15} m, or 100,000 times smaller than the atom. That implies a huge density, on the order of 10^{15} g/cm^3, much greater than any macroscopic matter.

Based on the size and mass of the nucleus revealed by his experiment, as well as the mass of electrons, Rutherford proposed the **planetary model of the atom**. The planetary model of the atom pictures low-mass electrons orbiting a large-mass nucleus. The sizes of the electron orbits are large compared with the size of the nucleus, and most of the atom is a vacuum. The model is analogous to how low-mass planets in our solar system orbit the large-mass Sun. In the atom, the attractive Coulomb force is analogous to gravitation in the planetary system (see Figure 22.4).

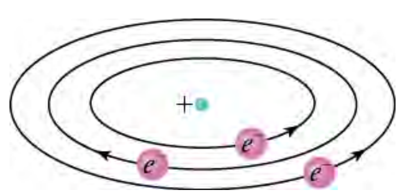


Figure 22.4 Rutherford's planetary model of the atom incorporates the characteristics of the nucleus, electrons, and the size of the atom. The model was the first to recognize the structure of atoms, in which low-mass electrons orbit a very small, massive nucleus in orbits much larger than the nucleus. The atom is mostly empty and is analogous to our planetary system.

Virtual Physics

Rutherford Scattering

Click to view content (https://www.openstax.org/l/28rutherford)

How did Rutherford figure out the structure of the atom without being able to see it? Explore the answer through this simulation of the famous experiment in which he disproved the plum pudding model by observing alpha particles bouncing off atoms and determining that they must have a small core.

TIPS FOR SUCCESS

As you progress through the model of the atom, consider the effect that experimentation has on the scientific process. Ask yourself the following: What would our model of the atom be without Rutherford's gold foil experiment? What further understanding of the atom would not have been gained? How would that affect our current technologies? Though often confusing, experiments taking place today to further understand composition of the atom could perhaps have a similar effect.

Absorption and Emission Spectra

In 1900, Max Planck recognized that all energy radiated from a source is emitted by atoms in quantum states. How would that radical idea relate to the interior of an atom? The answer was first found by investigating the spectrum of light or emission spectrum produced when a gas is highly energized.

Figure 22.5 shows how to isolate the emission spectrum of one such gas. The gas is placed in the discharge tube at the left, where it is energized to the point at which it begins to radiate energy or emit light. The radiated light is channeled by a thin slit and then passed through a diffraction grating, which will separate the light into its constituent wavelengths. The separated light will then strike the photographic film on the right.

The line spectrum shown in part (b) of Figure 22.5 is the output shown on the film for excited iron. Note that this spectrum is not continuous but discrete. In other words, only particular wavelengths are emitted by the iron source. Why would that be the case?

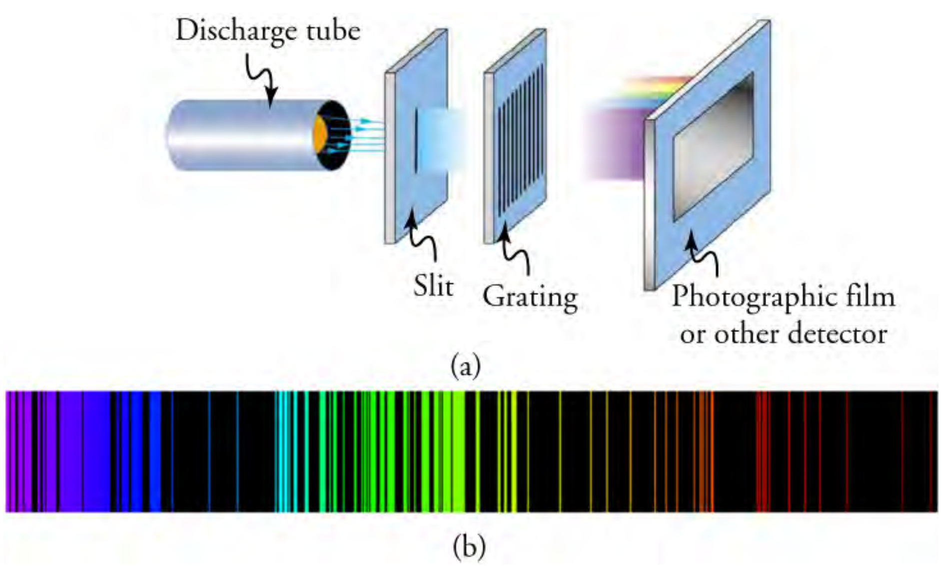


Figure 22.5 Part (a) shows, from left to right, a discharge tube, slit, and diffraction grating producing a line spectrum. Part (b) shows the emission spectrum for iron. The discrete lines imply quantized energy states for the atoms that produce them. The line spectrum for each element is unique, providing a powerful and much-used analytical tool, and many line spectra were well known for many years before they could be explained with physics. (credit:(b) Yttrium91, Wikimedia Commons)

The spectrum of light created by excited iron shows a variety of discrete wavelengths emitted within the visible spectrum. Each element, when excited to the appropriate degree, will create a discrete emission spectrum as in part (b) of Figure 22.5. However, the wavelengths emitted will vary from element to element. The emission spectrum for iron was chosen for Figure 22.5 solely because a substantial portion of its emission spectrum is within the visible spectrum. Figure 22.6 shows the emission spectrum for hydrogen. Note that, while discrete, a large portion of hydrogen emission takes place in the ultraviolet and infrared regions.

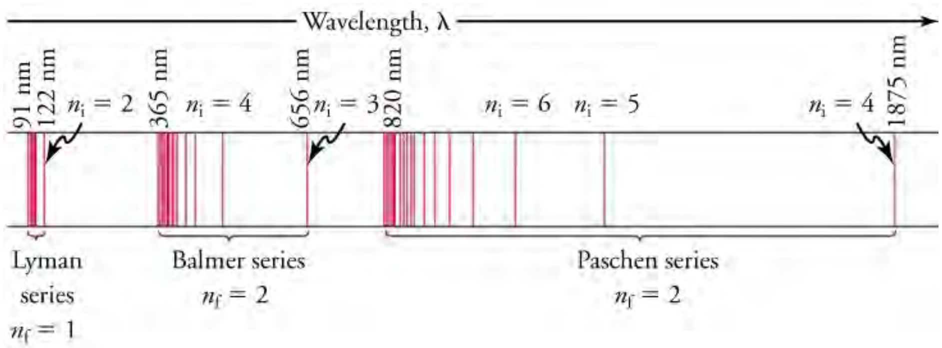


Figure 22.6 A schematic of the hydrogen spectrum shows several series named for those who contributed most to their determination. Part of the Balmer series is in the visible spectrum, while the Lyman series is entirely in the ultraviolet, and the Paschen series and others are in the infrared. Values of n_f and n_i are shown for some of the lines. Their importance will be described shortly.

Just as an emission spectrum shows all discrete wavelengths emitted by a gas, an absorption spectrum will show all light that is absorbed by a gas. Black lines exist where the wavelengths are absorbed, with the remainder of the spectrum lit by light is free to pass through. What relationship do you think exists between the black lines of a gas's absorption spectrum and the colored lines of its emission spectrum? Figure 22.7 shows the absorption spectrum of the Sun. The black lines are called **Fraunhofer lines**, and they correspond to the wavelengths absorbed by gases in the Sun's exterior.

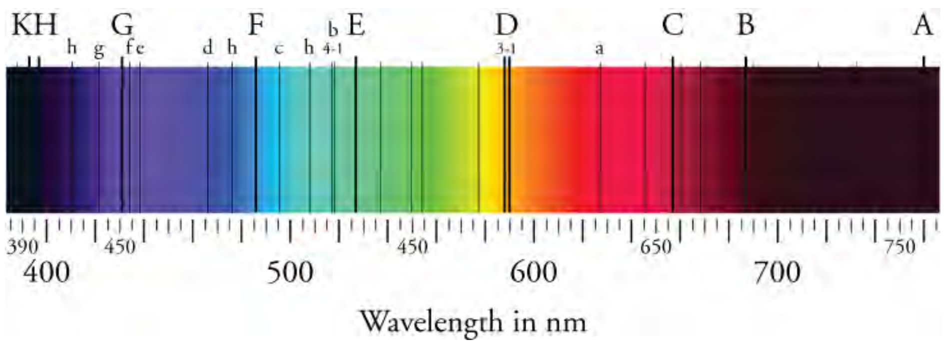


Figure 22.7 The absorption spectrum of the Sun. The black lines appear at wavelengths absorbed by the Sun's gas exterior. The energetic photons emitted from the Sun's interior are absorbed by gas in its exterior and reemitted in directions away from the observer. That results in dark lines within the absorption spectrum. The lines are called Fraunhofer lines, in honor of the German physicist who discovered them. Lines similar to those are used to determine the chemical composition of stars well outside our solar system.

Bohr's Explanation of the Hydrogen Spectrum

To tie the unique signatures of emission spectra to the composition of the atom itself would require clever thinking. Niels Bohr (1885–1962), a Danish physicist, did just that, by making immediate use of Rutherford's planetary model of the atom. Bohr, shown in Figure 22.8, became convinced of its validity and spent part of 1912 at Rutherford's laboratory. In 1913, after returning to Copenhagen, he began publishing his theory of the simplest atom, hydrogen, based on Rutherford's planetary model.

Figure 22.8 Niels Bohr, Danish physicist, used the planetary model of the atom to explain the atomic spectrum and size of the hydrogen

atom. His many contributions to the development of atomic physics and quantum mechanics, his personal influence on many students and colleagues, and his personal integrity, especially in the face of Nazi oppression, earned him a prominent place in history. (credit: Unknown Author, Wikimedia Commons)

Bohr was able to derive the formula for the hydrogen spectrum using basic physics, the planetary model of the atom, and some very important new conjectures. His first conjecture was that only certain orbits are allowed: In other words, in an atom, the orbits of electrons are quantized. Each quantized orbit has a different distinct energy, and electrons can move to a higher orbit by absorbing energy or drop to a lower orbit by emitting energy. Because of the quantized orbits, the amount of energy emitted or absorbed must also be quantized, producing the discrete spectra seen in Figure 22.5 and Figure 22.7. In equation form, the amount of energy absorbed or emitted can be found as

$$\Delta E = E_i - E_f, \tag{22.1}$$

where E_i refers to the energy of the initial quantized orbit, and E_f refers to the energy of the final orbits. Furthermore, the wavelength emitted can be found using the equation

$$hf = E_i - E_f, \tag{22.2}$$

and relating the wavelength to the frequency found using the equation $v = f\lambda$, where v corresponds to the speed of light.

It makes sense that energy is involved in changing orbits. For example, a burst of energy is required for a satellite to climb to a higher orbit. What is not expected is that atomic orbits should be quantized. Quantization is not observed for satellites or planets, which can have any orbit, given the proper energy (see Figure 22.9).

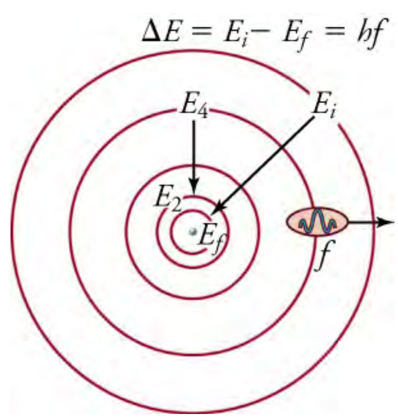


Figure 22.9 The planetary model of the atom, as modified by Bohr, has the orbits of the electrons quantized. Only certain orbits are allowed, explaining why atomic spectra are discrete or quantized. The energy carried away from an atom by a photon comes from the electron dropping from one allowed orbit to another and is thus quantized. The same is true for atomic absorption of photons.

Figure 22.10 shows an **energy-level diagram**, a convenient way to display energy states. Each of the horizontal lines corresponds to the energy of an electron in a different orbital. Energy is plotted vertically with the lowest or **ground state** at the bottom and with **excited states** above. The vertical arrow downwards shows energy being emitted out of the atom due to an electron dropping from one excited state to another. That would correspond to a line shown on the atom's emission spectrum. The Lyman series shown in Figure 22.6 results from electrons dropping to the ground state, while the Balmer and Paschen series result to electrons dropping to the $n = 2$ and $n = 3$ states, respectively.

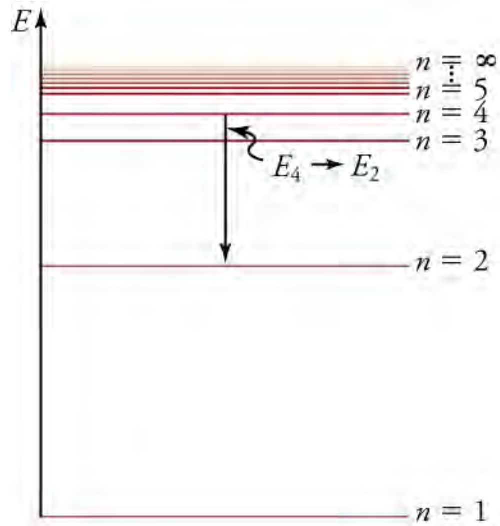


Figure 22.10 An energy-level diagram plots energy vertically and is useful in visualizing the energy states of a system and the transitions between them. This diagram is for the hydrogen-atom electrons, showing a transition between two orbits having energies E_4 and E_2 . The energy transition results in a Balmer series line in an emission spectrum.

Energy and Wavelength of Emitted Hydrogen Spectra

The energy associated with a particular orbital of a hydrogen atom can be found using the equation

$$E_n = -\frac{13.6\text{ eV}}{n^2}(n = 1, 2, 3, ...), \tag{22.3}$$

where n corresponds to the orbital value from the atom's nucleus. The negative value in the equation is based upon a baseline energy of zero when the electron is infinitely far from the atom. As a result, the negative value shows that energy is necessary to free the electron from its orbital state. The minimum energy to free the electron is also referred to as its *binding energy*. The equation is only valid for atoms with single electrons in their orbital shells (like hydrogen). For ionized atoms similar to hydrogen, the following formula may be used.

$$E_n = \frac{Z^2}{n^2}E_o\ (n = 1, 2, 3, ...) \tag{22.4}$$

Please note that E_o corresponds to –13.6 eV, as mentioned earlier. Additionally, Z refers to the atomic number of the element studied. The atomic number is the number of protons in the nucleus—it is different for each element. The above equation is derived from some basic physics principles, namely conservation of energy, conservation of angular momentum, Coulomb's law, and centripetal force. There are three derivations that result in the orbital energy equations, and they are shown below. While you can use the energy equations without understanding the derivations, they will help to remind you of just how valuable those fundamental concepts are.

Derivation 1 (Finding the Radius of an Orbital)

One primary difference between the planetary model of the solar system and the planetary model of the atom is the cause of the circular motion. While gravitation causes the motion of orbiting planets around an interior star, the Coulomb force is responsible for the circular shape of the electron's orbit. The magnitude of the centripetal force is $\frac{m_e v^2}{r_n}$, while the magnitude of the Coulomb force is $\frac{k(Zq_e)(q_e)}{{r_e}^2}$. The assumption here is that the nucleus is more massive than the stationary electron, and the electron orbits about it. That is consistent with the planetary model of the atom. Equating the Coulomb force and the centripetal force,

$$\frac{m_e v^2}{r_n} = \frac{k(Zq_e)(q_e)}{{r_e}^2}, \tag{22.5}$$

which yields

$$r_n = \frac{k\left(Zq_e{}^2\right)}{mv^2}. \tag{22.6}$$

Derivation 2 (Finding the Velocity of the Orbiting Electron)

Bohr was clever enough to find a way to calculate the electron orbital energies in hydrogen. That was an important first step that has been improved upon, but it is well worth repeating here, because it does correctly describe many characteristics of hydrogen. Assuming circular orbits, Bohr proposed that the angular momentum L of an electron in its orbit is also quantized, that is, it has only specific, discrete values. The value for L is given by the formula

$$L = m_e v r_n = n\frac{h}{2\pi}(n = 1, 2, 3, \ldots), \tag{22.7}$$

where L is the angular momentum, m_e is the electron's mass, r_n is the radius of the n th orbit, and h is Planck's constant. Note that angular momentum is $L = I\omega$. For a small object at a radius r, $I = mr^2$, and $\omega = \frac{v}{r}$, so that $L = I\omega = \left(mr^2\right)\left(\frac{v}{r}\right) = mvr$. Quantization says that the value of mvr can only be equal to h / 2, 2h / 2, 3h / 2, etc. At the time, Bohr himself did not know why angular momentum should be quantized, but by using that assumption, he was able to calculate the energies in the hydrogen spectrum, something no one else had done at the time.

Derivation 3 (Finding the Energy of the Orbiting Electron)

To get the electron orbital energies, we start by noting that the electron energy is the sum of its kinetic and potential energy.

$$E_n = KE + PE \tag{22.8}$$

Kinetic energy is the familiar $KE = \frac{1}{2}mv^2$, assuming the electron is not moving at a relativistic speed. Potential energy for the electron is electrical, or $PE = q_e V$, where V is the potential due to the nucleus, which looks like a point charge. The nucleus has a positive charge Zq_e ; thus, $V = \frac{kZq_e}{r_n}$, recalling an earlier equation for the potential due to a point charge from the chapter on Electricity and Magnetism. Since the electron's charge is negative, we see that $PE = \frac{-kZq_e{}^2}{r_n}$. Substituting the expressions for KE and PE,

$$E_n = \frac{1}{2}m_e v^2 - \frac{kZq_e{}^2}{r_n}. \tag{22.9}$$

Now we solve for r_n and v using the equation for angular momentum $L = m_e v r_n = n\frac{h}{2\pi}(n = 1, 2, 3, \ldots)$, giving

$$v = n\frac{h}{2\pi m_e r_n}(n = 1, 2, 3, \ldots) \tag{22.10}$$

and

$$r_n = n\frac{h}{2\pi m_e v}(n = 1, 2, 3, \ldots). \tag{22.11}$$

Substituting the expression for r_n and v into the above expressions for energy (KE and PE), and performing algebraic manipulation, yields

$$E_n = -\frac{Z^2}{n^2}E_o(n = 1, 2, 3, \ldots) \tag{22.12}$$

for the orbital energies of **hydrogen-like atoms**. Here, E_o is the ground-state energy ($n = 1$) for hydrogen ($Z = 1$) and is given by

$$E_o = \frac{2\pi^2 q_e{}^4 m_e k^2}{h^2} = 13.6 \text{ eV}. \tag{22.13}$$

Thus, for hydrogen,

$$E_n = -\frac{13.6 \text{ eV}}{n^2}(n = 1, 2, 3, \ldots). \tag{22.14}$$

The relationship between orbital energies and orbital states for the hydrogen atom can be seen in Figure 22.11.

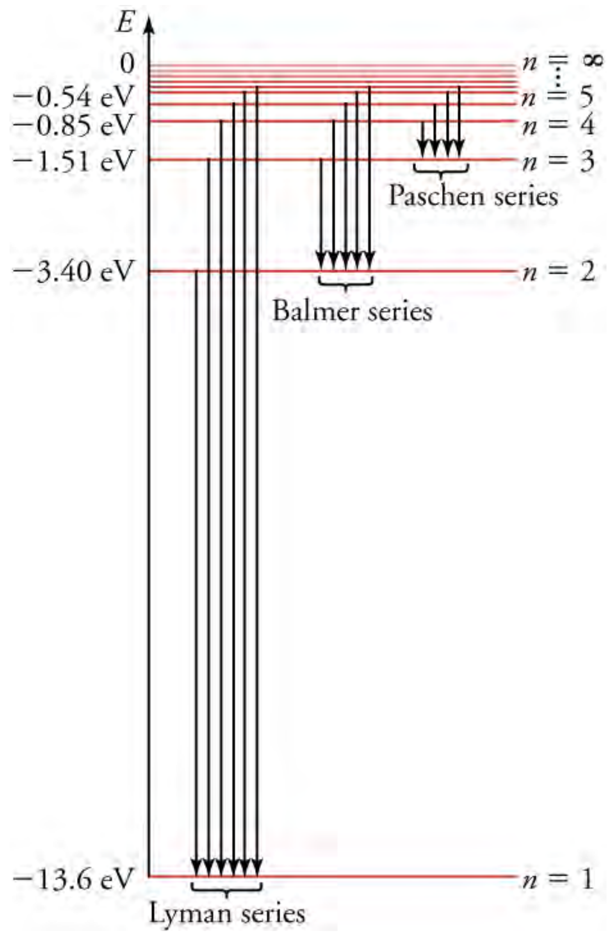


Figure 22.11 Energy-level diagram for hydrogen showing the Lyman, Balmer, and Paschen series of transitions. The orbital energies are calculated using the above equation, first derived by Bohr.

WORKED EXAMPLE

A hydrogen atom is struck by a photon. How much energy must be absorbed from the photon to raise the electron of the hydrogen atom from its ground state to its second orbital?

Strategy

The hydrogen atom has an atomic number of $Z = 1$. Raising the electron from the ground state to its second orbital will increase its orbital level from $n = 1$ to $n = 2$. The energy determined will be measured in electron-volts.

Solution

The amount of energy necessary to cause the change in electron state is the difference between the final and initial energies of the electron. The final energy state of the electron can be found using

$$E_n = \frac{Z^2}{n^2} E_o \; (n = 1, 2, 3, \ldots) . \tag{22.15}$$

Knowing the n and Z values for the hydrogen atom, and knowing that $E_o = -13.6$ eV, the result is

$$E_f = \frac{1^2}{2^2}(-13.6 \text{ eV}) = -3.4 \text{ eV}. \tag{22.16}$$

The original amount of energy associated with the electron is equivalent to the ground state orbital, or

$$E_O = \frac{1^2}{1^2}(-13.6 \text{ eV}) = -13.6 \text{ eV}. \tag{22.17}$$

The amount of energy necessary to change the orbital state of the electron can be found by determining the electron's change in energy.

$$\Delta E = E_f - E_o = (-3.4 \text{ eV}) - (-13.6 \text{ eV}) = +10.2 \text{ eV} \tag{22.18}$$

Discussion

The energy required to change the orbital state of the electron is positive. That means that for the electron to move to a state with greater energy, energy must be added to the atom. Should the electron drop back down to its original energy state, a change of −10.2 eV would take place, and 10.2 eV of energy would be emitted from the atom. Just as only quantum amounts of energy may be absorbed by the atom, only quantum amounts of energy can be emitted from the atom. That helps to explain many of the quantum light effects that you have learned about previously.

WORKED EXAMPLE

Characteristic X-Ray Energy

Calculate the approximate energy of an X-ray emitted for an $n = 2$ to $n = 1$ transition in a tungsten anode in an X-ray tube.

Strategy

How do we calculate energies in a multiple-electron atom? In the case of characteristic X-rays, the following approximate calculation is reasonable. Characteristic X-rays are produced when an inner-shell vacancy is filled. Inner-shell electrons are nearer the nucleus than others in an atom and thus feel little net effect from the others. That is similar to what happens inside a charged conductor, where its excess charge is distributed over the surface so that it produces no electric field inside. It is reasonable to assume the inner-shell electrons have hydrogen-like energies, as given by

$$E_n = \frac{Z^2}{n^2} E_o \; (n = 1, 2, 3, \ldots) \tag{22.19}$$

For tungsten, $Z = 74$, so that the effective charge is 73.

Solution

The amount of energy given off as an X-ray is found using

$$\Delta E = hf = E_i - E_f, \tag{22.20}$$

where

$$E_f = -\frac{Z^2}{1^2} E_o = -\frac{73^2}{1}(13.6 \text{ eV}) = -72.5 \text{ keV} \tag{22.21}$$

and

$$E_i = -\frac{Z^2}{2^2} E_o = -\frac{73^2}{4}(13.6 \text{ eV}) = -18.1 \text{ keV}. \tag{22.22}$$

Thus,

$$\Delta E = E_i - E_f = (-18.1 \text{ keV}) - (-72.5 \text{ keV}) = 54.4 \text{ keV}. \tag{22.23}$$

Discussion

This large photon energy is typical of characteristic X-rays from heavy elements. It is large compared with other atomic emissions because it is produced when an inner-shell vacancy is filled, and inner-shell electrons are tightly bound. Characteristic X-ray energies become progressively larger for heavier elements because their energy increases approximately as Z^2. Significant accelerating voltage is needed to create such inner-shell vacancies, because other shells are filled and you cannot simply bump one electron to a higher filled shell. You must remove it from the atom completely. In the case of tungsten, at least 72.5 kV is needed. Tungsten is a common anode material in X-ray tubes; so much of the energy of the impinging electrons is absorbed, raising its temperature, that a high-melting-point material like tungsten is required.

The wavelength of light emitted by an atom can also be determined through basic derivations. Let us consider the energy of a photon emitted from a hydrogen atom in a downward transition, given by the equation

$$\Delta E = hf = E_i - E_f \tag{22.24}$$

Substituting $E_n = \left(\frac{-13.6\text{ eV}}{n^2}\right)$, we get

$$hf = (13.6\text{ eV})\left(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2}\right). \tag{22.25}$$

Dividing both sides of the equation by hc gives us an expression for $\frac{1}{\lambda}$,

$$\frac{hf}{hc} = \frac{f}{c} = \frac{1}{\lambda} = \frac{13.6\text{ eV}}{hc}\left(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2}\right). \tag{22.26}$$

It can be shown that

$$\left(\frac{13.6\text{ eV}}{hc}\right) = \frac{(13.6\text{ eV})(1.602 \times 10^{-19}\text{J/eV})}{(6.602 \times 10^{-34}\text{J} \cdot \text{s})(2.998 \times 10^{8}\text{m/s})} = 1.097 \times 10^{7}\text{m}^{-1} = R, \tag{22.27}$$

where R is the **Rydberg constant**.

Simplified, the formula for determining emitted wavelength can now be written as

$$\frac{1}{\lambda} = R\left(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2}\right). \tag{22.28}$$

WORKED EXAMPLE

What wavelength of light is emitted by an electron dropping from the third orbital to the ground state of a hydrogen atom?

Strategy

The ground state of a hydrogen atom is considered the first orbital of the atom. As a result, $n_f = 1$ and $n_i = 3$. The Rydberg constant has already been determined and will be constant regardless of atom chosen.

Solution

$$\frac{1}{\lambda} = R\left(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2}\right) \tag{22.29}$$

For the equation above, calculate wavelength based on the known energy states.

$$\frac{1}{\lambda} = 1.097 \times 10^{7}\left(\frac{1}{1^2} - \frac{1}{3^2}\right) = 9.751 \times 10^{6}\text{m}^{-1} \tag{22.30}$$

Rearranging the equation for wavelength yields

$$\lambda = 1.026 \times 10^{-7}\text{m} = 102.6\text{ nm}. \tag{22.31}$$

Discussion

This wavelength corresponds to light in the ultraviolet spectrum. As a result, we would not be able to see the photon of light emitted when an electron drops from its third to first energy state. However, it is worth noting that by supplying light of wavelength precisely 102.6 nm, we can cause the electron in hydrogen to move from its first to its third orbital state.

Limits of Bohr's Theory and the Quantum Model of the Atom

There are limits to Bohr's theory. It does not account for the interaction of bound electrons, so it cannot be fully applied to multielectron atoms, even one as simple as the two-electron helium atom. Bohr's model is what we call *semiclassical*. The orbits are quantized (nonclassical) but are assumed to be simple circular paths (classical). As quantum mechanics was developed, it became clear that there are no well-defined orbits; rather, there are clouds of probability. Additionally, Bohr's theory did not explain that some spectral lines are doublets or split into two when examined closely. While we shall examine a few of those aspects of quantum mechanics in more detail, it should be kept in mind that Bohr did not fail. Rather, he made very important steps along the path to greater knowledge and laid the foundation for all of atomic physics that has since evolved.

DeBroglie's Waves

Following Bohr's initial work on the hydrogen atom, a decade was to pass before Louis de Broglie proposed that matter has wave properties. The wave-like properties of matter were subsequently confirmed by observations of electron interference when scattered from crystals. Electrons can exist only in locations where they interfere constructively. How does that affect electrons in atomic orbits? When an electron is bound to an atom, its wavelength must fit into a small space, something like a standing wave on a string (see Figure 22.12). Orbits in which an electron can constructively interfere with itself are allowed. All orbits in which constructive interference cannot occur are not able to exist. Thus, only certain orbits are allowed. The wave nature of an electron, according to de Broglie, is why the orbits are quantized!

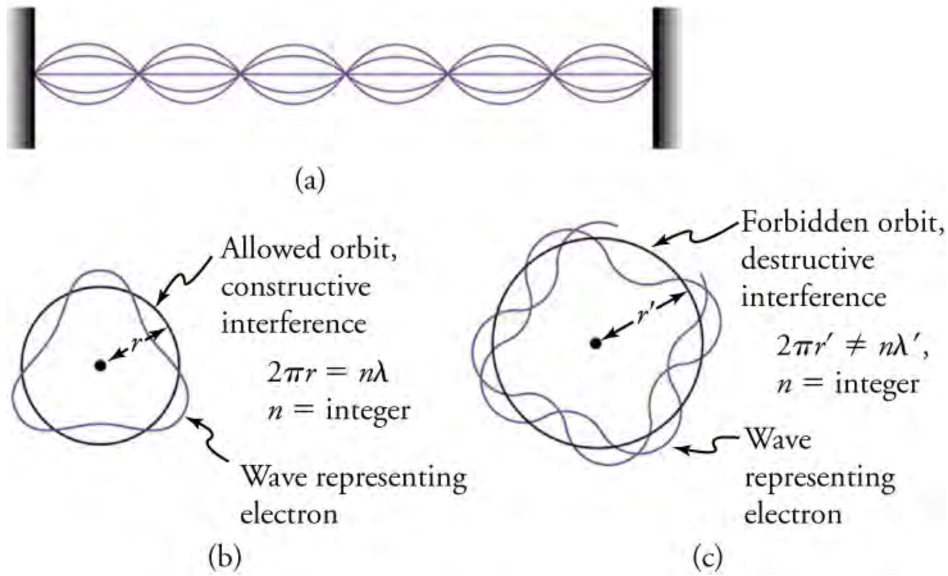


Figure 22.12 (a) Standing waves on a string have a wavelength related to the length of the string, allowing them to interfere constructively. (b) If we imagine the string formed into a closed circle, we get a rough idea of how electrons in circular orbits can interfere constructively. (c) If the wavelength does not fit into the circumference, the electron interferes destructively; it cannot exist in such an orbit.

For a circular orbit, constructive interference occurs when the electron's wavelength fits neatly into the circumference, so that wave crests always align with crests and wave troughs align with troughs, as shown in Figure 22.12(b). More precisely, when an integral multiple of the electron's wavelength equals the circumference of the orbit, constructive interference is obtained. In equation form, the condition for constructive interference and an allowed electron orbit is

$$n\lambda_n = 2\pi r_n (n = 1, 2, 3, ...), \tag{22.32}$$

where λ_n is the electron's wavelength and r_n is the radius of that circular orbit. Figure 22.13 shows the third and fourth orbitals of a hydrogen atom.

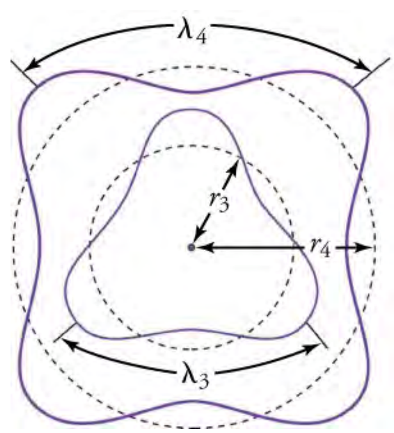


Figure 22.13 The third and fourth allowed circular orbits have three and four wavelengths, respectively, in their circumferences.

Heisenberg Uncertainty

How does determining the location of an electron change its trajectory? The answer is fundamentally important—measurement affects the system being observed. It is impossible to measure a physical quantity exactly, and greater precision in measuring one quantity produces less precision in measuring a related quantity. It was Werner Heisenberg who first stated that limit to knowledge in 1929 as a result of his work on quantum mechanics and the wave characteristics of all particles (see Figure 22.14).

Figure 22.14 Werner Heisenberg was the physicist who developed the first version of true quantum mechanics. Not only did his work give a description of nature on the very small scale, it also changed our view of the availability of knowledge. Although he is universally recognized for the importance of his work by receiving the Nobel Prize in 1932, for example, Heisenberg remained in Germany during World War II and headed the German effort to build a nuclear bomb, permanently alienating himself from most of the scientific community. (credit: Unknown Author, Wikimedia Commons)

For example, you can measure the position of a moving electron by scattering light or other electrons from it. However, by doing so, you are giving the electron energy, and therefore imparting momentum to it. As a result, the momentum of the electron is affected and cannot be determined precisely. This change in momentum could be anywhere from close to zero up to the relative momentum of the electron ($p \approx h/\lambda$). Note that, in this case, the particle is an electron, but the principle applies to any particle.

Viewing the electron through the model of wave-particle duality, Heisenberg recognized that, because a wave is not located at one fixed point in space, there is an uncertainty associated with any electron's position. That uncertainty in position, Δx , is approximately equal to the wavelength of the particle. That is, $\Delta x \approx \lambda$. There is an interesting trade-off between position and momentum. The uncertainty in an electron's position can be reduced by using a shorter-wavelength electron, since $\Delta x \approx \lambda$. But shortening the wavelength increases the uncertainty in momentum, since $\Delta p \approx h/\lambda$. Conversely, the uncertainty in momentum can be reduced by using a longer-wavelength electron, but that increases the uncertainty in position. Mathematically, you can express the trade-off by multiplying the uncertainties. The wavelength cancels, leaving

$$\Delta x \Delta p \approx h.$$

Therefore, if one uncertainty is reduced, the other must increase so that their product is $\approx h$. With the use of advanced mathematics, Heisenberg showed that the best that can be done in a simultaneous measurement of position and momentum is

$$\Delta x \Delta p \geq \frac{h}{4\pi}. \tag{22.33}$$

That relationship is known as the **Heisenberg uncertainty principle**.

The Quantum Model of the Atom

Because of the wave characteristic of matter, the idea of well-defined orbits gives way to a model in which there is a cloud of probability, consistent with Heisenberg's uncertainty principle. Figure 22.15 shows how the principle applies to the ground state of hydrogen. If you try to follow the electron in some well-defined orbit using a probe that has a wavelength small enough to measure position accurately, you will instead knock the electron out of its orbit. Each measurement of the electron's position will find it to be in a definite location somewhere near the nucleus. Repeated measurements reveal a cloud of probability like that in the figure, with each speck the location determined by a single measurement. There is not a well-defined, circular-orbit type of distribution. Nature again proves to be different on a small scale than on a macroscopic scale.

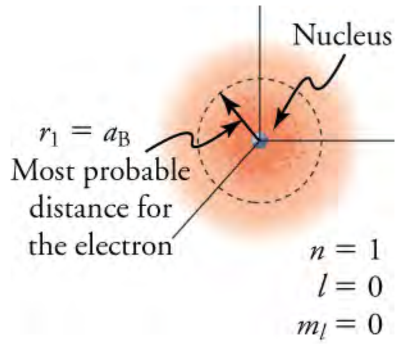


Figure 22.15 The ground state of a hydrogen atom has a probability cloud describing the position of its electron. The probability of finding the electron is proportional to the darkness of the cloud. The electron can be closer or farther than the Bohr radius, but it is very unlikely to be a great distance from the nucleus.

Virtual Physics

Models of the Hydrogen Atom

Click to view content (https://www.openstax.org/l/28atom_model)

How did scientists figure out the structure of atoms without looking at them? Try out different models by shooting light at the atom. Use this simulation to see how the prediction of the model matches the experimental results.

Check Your Understanding

1. Alpha particles are positively charged. What influence did their charge have on the gold foil experiment?
   a. The positively charged alpha particles were attracted by the attractive electrostatic force from the positive nuclei of the gold atoms.
   b. The positively charged alpha particles were scattered by the attractive electrostatic force from the positive nuclei of the gold atoms.
   c. The positively charged alpha particles were scattered by the repulsive electrostatic force from the positive nuclei of the gold atoms.
   d. The positively charged alpha particles were attracted by the repulsive electrostatic force from the positive nuclei of the gold atoms.

22.2 Nuclear Forces and Radioactivity

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe the structure and forces present within the nucleus
- Explain the three types of radiation
- Write nuclear equations associated with the various types of radioactive decay

Section Key Terms

alpha decay	atomic number	beta decay	gamma decay	Geiger tube
isotope	mass number	nucleons	radioactive	radioactive decay

radioactivity scintillator strong nuclear force transmutation

There is an ongoing quest to find the substructures of matter. At one time, it was thought that atoms would be the ultimate substructure. However, just when the first direct evidence of atoms was obtained, it became clear that they have a substructure and a tiny nucleus. The nucleus itself has spectacular characteristics. For example, certain nuclei are unstable, and their decay emits radiations with energies millions of times greater than atomic energies. Some of the mysteries of nature, such as why the core of Earth remains molten and how the Sun produces its energy, are explained by nuclear phenomena. The exploration of radioactivity and the nucleus has revealed new fundamental particles, forces, and conservation laws. That exploration has evolved into a search for further underlying structures, such as quarks. In this section, we will explore the fundamentals of the nucleus and nuclear radioactivity.

The Structure of the Nucleus

At this point, you are likely familiar with the neutron and proton, the two fundamental particles that make up the nucleus of an atom. Those two particles, collectively called **nucleons**, make up the small interior portion of the atom. Both particles have nearly the same mass, although the neutron is about two parts in 1,000 more massive. The mass of a proton is equivalent to 1,836 electrons, while the mass of a neutron is equivalent to that of 1,839 electrons. That said, each of the particles is significantly more massive than the electron.

When describing the mass of objects on the scale of nucleons and atoms, it is most reasonable to measure their mass in terms of atoms. The atomic mass unit (u) was originally defined so that a neutral carbon atom would have a mass of exactly 12 u. Given that protons and neutrons are approximately the same mass, that there are six protons and six neutrons in a carbon atom, and that the mass of an electron is minuscule in comparison, measuring this way allows for both protons and neutrons to have masses close to 1 u. Table 22.1 shows the mass of protons, neutrons, and electrons on the new scale.

TIPS FOR SUCCESS

For most conceptual situations, the difference in mass between the proton and neutron is insubstantial. In fact, for calculations that require fewer than four significant digits, both the proton and neutron masses may be considered equivalent to one atomic mass unit. However, when determining the amount of energy released in a nuclear reaction, as in Equation 22.40, the difference in mass cannot be ignored.

Another other useful mass unit on the atomic scale is the MeV/c^2 . While rarely used in most contexts, it is convenient when one uses the equation $E = mc^2$, as will be addressed later in this text.

	Proton Mass	Neutron Mass	Electron Mass
Kilograms (kg)	1.673×10^{-27}	1.675×10^{-27}	9.109×10^{-31}
Atomic mass units (u)	1.007	1.009	5.486×10^{-4}

Table 22.1 Atomic Masses for Multiple Units

To more completely characterize nuclei, let us also consider two other important quantities: the atomic number and the mass number. The **atomic number**, Z, represents the number of protons within a nucleus. That value determines the elemental quality of each atom. Every carbon atom, for instance, has a Z value of 6, whereas every oxygen atom has a Z value of 8. For clarification, only oxygen atoms may have a Z value of 8. If the Z value is not 8, the atom cannot be oxygen.

The **mass number**, A, represents the total number of protons and neutrons, or nucleons, within an atom. For an ordinary carbon atom the mass number would be 12, as there are typically six neutrons accompanying the six protons within the atom. In the case of carbon, the mass would be exactly 12 u. For oxygen, with a mass number of 16, the atomic mass is 15.994915 u. Of course, the difference is minor and can be ignored for most scenarios. Again, because the mass of an electron is so small compared to the nucleons, the mass number and the atomic mass can be essentially equivalent. Figure 22.16 shows an example of Lithium-7, which has an atomic number of 3 and a mass number of 7.

How does the mass number help to differentiate one atom from another? If each atom of carbon has an atomic number of 6, then what is the value of including the mass number at all? The intent of the mass number is to differentiate between various isotopes of an atom. The term **isotope** refers to the variation of atoms based upon the number of neutrons within their nucleus. While it is most common for there to be six neutrons accompanying the six protons within a carbon atom, it is possible to find carbon atoms with seven neutrons or eight neutrons. Those carbon atoms are respectively referred to as carbon-13 and carbon-14 atoms, with their mass numbers being their primary distinction. The isotope distinction is an important one to make, as the number of neutrons within an atom can affect a number of its properties, not the least of which is nuclear stability.

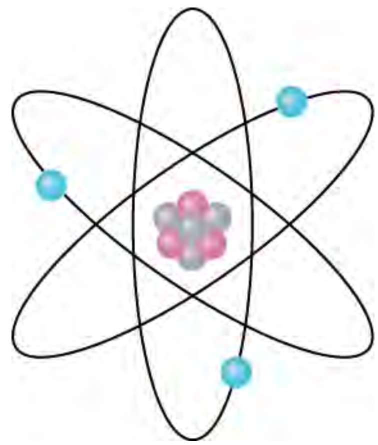


Figure 22.16 Lithium-7 has three protons and four neutrons within its nucleus. As a result, its mass number is 7, while its atomic number is 3. The actual mass of the atom is 7.016 u. Lithium 7 is an isotope of lithium.

To more easily identify various atoms, their atomic number and mass number are typically written in a form of representation called the nuclide. The nuclide form appears as follows: $^{Z}_{A}X_{N}$, where *X* is the atomic symbol and *N* represents the number of neutrons.

Let us look at a few examples of nuclides expressed in the $^{Z}_{A}X_{N}$ notation. The nucleus of the simplest atom, hydrogen, is a single proton, or $^{1}_{1}\text{H}$ (the zero for no neutrons is often omitted). To check the symbol, refer to the periodic table—you see that the atomic number *Z* of hydrogen is 1. Since you are given that there are no neutrons, the mass number *A* is also 1. There is a scarce form of hydrogen found in nature called *deuterium*; its nucleus has one proton and one neutron and, hence, twice the mass of common hydrogen. The symbol for deuterium is, thus, $^{2}_{1}\text{H}_2$. An even rarer—and radioactive—form of hydrogen is called *tritium*, since it has a single proton and two neutrons, and it is written $^{3}_{1}\text{H}_2$. The three varieties of hydrogen have nearly identical chemistries, but the nuclei differ greatly in mass, stability, and other characteristics. Again, the different nuclei are referred to as isotopes of the same element.

There is some redundancy in the symbols *A*, *X*, *Z*, and *N*. If the element *X* is known, then *Z* can be found in a periodic table. If both *A* and *X* are known, then *N* can also be determined by first finding *Z*; then, *N* = *A* – *Z*. Thus the simpler notation for nuclides is

$$^{A}X, \tag{22.34}$$

which is sufficient and is most commonly used. For example, in this simpler notation, the three isotopes of hydrogen are ^{1}H, ^{2}H, and ^{3}H . For ^{238}U, should we need to know, we can determine that *Z* = 92 for uranium from the periodic table, and thus, *N* = 238 – 92 = 146.

Radioactivity and Nuclear Forces

In 1896, the French physicist Antoine Henri Becquerel (1852–1908) noticed something strange. When a uranium-rich mineral called pitchblende was placed on a completely opaque envelope containing a photographic plate, it darkened spots on the photographic plate.. Becquerel reasoned that the pitchblende must emit invisible rays capable of penetrating the opaque material. Stranger still was that no light was shining on the pitchblende, which means that the pitchblende was emitting the invisible rays continuously without having any energy input! There is an apparent violation of the law of conservation of energy, one that scientists can now explain using Einstein's famous equation $E = mc^2$. It was soon evident that Becquerel's rays originate in the nuclei of the atoms and have other unique characteristics.

To this point, most reactions you have studied have been chemical reactions, which are reactions involving the electrons surrounding the atoms. However, two types of experimental evidence implied that Becquerel's rays did not originate with electrons, but instead within the nucleus of an atom.

First, the radiation is found to be only associated with certain elements, such as uranium. Whether uranium was in the form of an element or compound was irrelevant to its radiation. In addition, the presence of radiation does not vary with temperature, pressure, or ionization state of the uranium atom. Since all of those factors affect electrons in an atom, the radiation cannot come from electron transitions, as atomic spectra do.

The huge energy emitted during each event is the second piece of evidence that the radiation cannot be atomic. Nuclear radiation has energies on the order of 10^6 eV per event, which is much greater than typical atomic energies that are a few eV, such as those observed in spectra and chemical reactions, and more than ten times as high as the most energetic X-rays.

But why would reactions within the nucleus take place? And what would cause an apparently stable structure to begin emitting energy? Was there something special about Becquerel's uranium-rich pitchblende? To answer those questions, it is necessary to look into the structure of the nucleus. Though it is perhaps surprising, you will find that many of the same principles that we observe on a macroscopic level still apply to the nucleus.

Nuclear Stability

A variety of experiments indicate that a nucleus behaves something like a tightly packed ball of nucleons, as illustrated in Figure 22.17. Those nucleons have large kinetic energies and, thus, move rapidly in very close contact. Nucleons can be separated by a large force, such as in a collision with another nucleus, but strongly resist being pushed closer together. The most compelling evidence that nucleons are closely packed in a nucleus is that the radius of a nucleus, r, is found to be approximately

$$r = r_o A^{1/3}, \tag{22.35}$$

where $r_o = 1.2$ femtometer (fm) and A is the mass number of the nucleus.

Note that $r^3 \propto A$. Since many nuclei are spherical, and the volume of a sphere is $V = \left(\frac{4}{3}\right)\pi r^3$, we see that $V \propto A$—that is, the volume of a nucleus is proportional to the number of nucleons in it. That is what you expect if you pack nucleons so close that there is no empty space between them.

Figure 22.17 Nucleons are held together by nuclear forces and resist both being pulled apart and pushed inside one another. The volume of the nucleus is the sum of the volumes of the nucleons in it, here shown in different colors to represent protons and neutrons.

So what forces hold a nucleus together? After all, the nucleus is very small and its protons, being positive, should exert tremendous repulsive forces on one another. Considering that, it seems that the nucleus would be forced apart, not together!

The answer is that a previously unknown force holds the nucleus together and makes it into a tightly packed ball of nucleons. This force is known as the **strong nuclear force**. The strong force has such a short range that it quickly fall to zero over a distance of only 10^{-15} meters. However, like glue, it is very strong when the nucleons get close to one another.

The balancing of the electromagnetic force with the nuclear forces is what allows the nucleus to maintain its spherical shape. If, for any reason, the electromagnetic force should overcome the nuclear force, components of the nucleus would be projected outward, creating the very radiation that Becquerel discovered!

Understanding why the nucleus would break apart can be partially explained using Table 22.2. The balance between the strong nuclear force and the electromagnetic force is a tenuous one. Recall that the attractive strong nuclear force exists between any two nucleons and acts over a very short range while the weaker repulsive electromagnetic force only acts between protons, although over a larger range. Considering the interactions, an imperfect balance between neutrons and protons can result in a nuclear reaction, with the result of regaining equilibrium.

	Range of Force	Direction	Nucleon Interaction	Magnitude of Force
Electromagnetic Force	Long range, though decreasing by $1/r^2$	Repulsive	Proton –proton repulsion	Relatively small
Strong Nuclear Force	Very short range, essentially zero at 1 femtometer	Attractive	Attraction between any two nucleons	100 times greater than the electromagnetic force

Table 22.2 Comparing the Electromagnetic and Strong Forces

The radiation discovered by Becquerel was due to the large number of protons present in his uranium-rich pitchblende. In short, the large number of protons caused the electromagnetic force to be greater than the strong nuclear force. To regain stability, the nucleus needed to undergo a nuclear reaction called **alpha (α) decay**.

The Three Types of Radiation

Radioactivity refers to the act of emitting particles or energy from the nucleus. When the uranium nucleus emits energetic nucleons in Becquerel's experiment, the radioactive process causes the nucleus to alter in structure. The alteration is called **radioactive decay**. Any substance that undergoes radioactive decay is said to be **radioactive**. That those terms share a root with the term *radiation* should not be too surprising, as they all relate to the transmission of energy.

Alpha Decay

Alpha decay refers to the type of decay that takes place when too many protons exist in the nucleus. It is the most common type of decay and causes the nucleus to regain equilibrium between its two competing internal forces. During alpha decay, the nucleus ejects two protons and two neutrons, allowing the strong nuclear force to regain balance with the repulsive electromagnetic force. The nuclear equation for an alpha decay process can be shown as follows.

$$^{A}_{Z}X_N \rightarrow {}^{A-4}_{Z-2}Y_N + {}^{4}_{2}\mathrm{He} \tag{22.36}$$

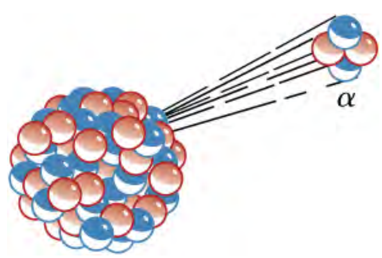


Figure 22.18 A nucleus undergoes alpha decay. The alpha particle can be seen as made up of two neutrons and two protons, which constitute a helium-4 atom.

Three things to note as a result of the above equation:

1. By ejecting an alpha particle, the original nuclide decreases in atomic number. That means that Becquerel's uranium nucleus, upon decaying, is actually transformed into thorium, two atomic numbers lower on the periodic table! The process of changing elemental composition is called **transmutation**.
2. Note that the two protons and two neutrons ejected from the nucleus combine to form a helium nucleus. Shortly after decay, the ejected helium ion typically acquires two electrons to become a stable helium atom.
3. Finally, it is important to see that, despite the elemental change, physical conservation still takes place. The mass number of the new element and the alpha particle together equal the mass number of the original element. Also, the net charge of all particles involved remains the same before and after the transmutation.

Beta Decay

Like alpha decay, **beta (β) decay** also takes place when there is an imbalance between neutrons and protons within the nucleus. For beta decay, however, a neutron is transformed into a proton and electron or vice versa. The transformation allows for the total mass number of the atom to remain the same, although the atomic number will increase by one (or decrease by one). Once again, the transformation of the neutron allows for a rebalancing of the strong nuclear and electromagnetic forces. The nuclear equation for a beta decay process is shown below.

$${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+1}Y_{N-1} + e + v$$

The symbol v in the equation above stands for a high-energy particle called the neutrino. A nucleus may also emit a positron, and in that case Z decreases and N increases. It is beyond the scope of this section and will be discussed in further detail in the chapter on particles. It is worth noting, however, that the mass number and charge in all beta-decay reactions are conserved.

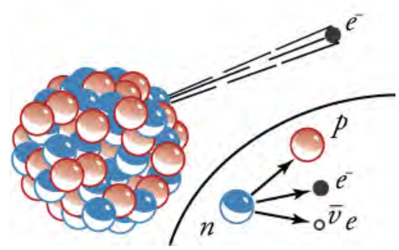


Figure 22.19 A nucleus undergoes beta decay. The neutron splits into a proton, electron, and neutrino. This particular decay is called β^{-} decay.

Gamma Decay

Gamma decay is a unique form of radiation that does not involve balancing forces within the nucleus. Gamma decay occurs when a nucleus drops from an excited state to the ground state. Recall that such a change in energy state will release energy from the nucleus in the form of a photon. The energy associated with the photon emitted is so great that its wavelength is shorter than that of an X-ray. Its nuclear equation is as follows.

$${}^{A}_{Z}X_{N} \rightarrow X_{N} + \gamma \tag{22.37}$$

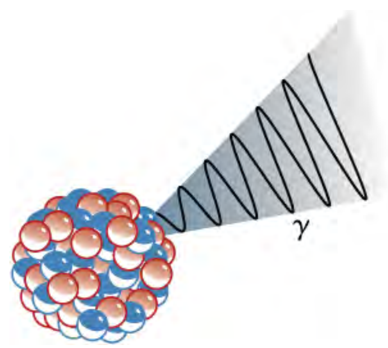


Figure 22.20 A nucleus undergoes gamma decay. The nucleus drops in energy state, releasing a gamma ray.

WORKED EXAMPLE

Creating a Decay Equation

Write the complete decay equation in ${}^{A}_{Z}X_{N}$ notation for beta decay producing ${}^{137}\mathrm{Ba}$. Refer to the periodic table for values of Z.

Strategy

Beta decay results in an increase in atomic number. As a result, the original (or parent) nucleus, must have an atomic number of one fewer proton.

Solution

The equation for beta decay is as follows

$${}^{A}_{Z}X_{N} \rightarrow {}_{Z+1}{}^{A}Y_{N-1} + e + v. \tag{22.38}$$

Considering that barium is the product (or daughter) nucleus and has an atomic number of 56, the original nucleus must be of an atomic number of 55. That corresponds to cesium, or Cs.

$${}^{137}_{55}\mathrm{Cs}_{N} \rightarrow {}^{137}_{56}\mathrm{Ba}_{N-1} + e + v \tag{22.39}$$

The number of neutrons in the parent cesium and daughter barium can be determined by subtracting the atomic number from the mass number (137 – 55 for cesium, 137 – 56 for barium). Substitute those values for the *N* and *N – 1* subscripts in the above equation.

$$^{137}_{55}\mathrm{Cs}_{82} \rightarrow {}^{137}_{56}\mathrm{Ba}_{81} + e + v \quad (22.40)$$

Discussion

The terms *parent* and *daughter* nucleus refer to the reactants and products of a nuclear reaction. The terminology is not just used in this example, but in all nuclear reaction examples. The cesium-137 nuclear reaction poses a significant health risk, as its chemistry is similar to that of potassium and sodium, and so it can easily be concentrated in your cells if ingested.

WORKED EXAMPLE

Alpha Decay Energy Found from Nuclear Masses

Find the energy emitted in the α decay of ^{239}Pu.

Strategy

Nuclear reaction energy, such as released in α decay, can be found using the equation $E = mc^2$. We must first find Δm, the difference in mass between the parent nucleus and the products of the decay.

The mass of pertinent particles is as follows

^{239}Pu: 239.052157 u

^{235}U: 235.043924 u

^{4}He: 4.002602 u.

Solution

The decay equation for ^{239}Pu is

$$^{239}\mathrm{Pu} \rightarrow {}^{235}\mathrm{U} + {}^{4}\mathrm{He}. \quad (22.41)$$

Determine the amount of mass lost between the parent and daughter nuclei.

$$\begin{aligned} \Delta m &= m\left(^{239}\mathrm{P\ u}\right) - \left(m\left(^{239}\mathrm{U}\right) + m\left(^{4}\mathrm{He}\right)\right) \\ \Delta m &= 239.052157\ \mathrm{u} - (235.043924\ \mathrm{u} + 4.002602\ \mathrm{u}) \\ \Delta m &= 0.0005631\ \mathrm{u} \end{aligned} \quad (22.42)$$

Now we can find *E* by entering Δm into the equation.

$$E = (\Delta m)\, c^2 = (0.005631\ \mathrm{u})\, c^2 \quad (22.43)$$

And knowing that $1\ \mathrm{u} = 931.5\ \mathrm{meV}/c^2$, we can find that

$$E = (0.005631)\left(931.5\ \mathrm{MeV}/c^2\right)\left(c^2\right) = 5.25\ \mathrm{MeV}. \quad (22.44)$$

Discussion

The energy released in this α decay is in the MeV range, about 10^6 times as great as typical chemical reaction energies, consistent with previous discussions. Most of the energy becomes kinetic energy of the α particle (or ^{4}He nucleus), which moves away at high speed.

The energy carried away by the recoil of the ^{235}U nucleus is much smaller, in order to conserve momentum. The ^{235}U nucleus can be left in an excited state to later emit photons (γ rays). The decay is spontaneous and releases energy, because the products have less mass than the parent nucleus.

Properties of Radiation

The charges of the three radiated particles differ. Alpha particles, with two protons, carry a net charge of +2. Beta particles, with one electron, carry a net charge of –1. Meanwhile, gamma rays are solely photons, or light, and carry no charge. The difference in charge plays an important role in how the three radiations affect surrounding substances.

Alpha particles, being highly charged, will quickly interact with ions in the air and electrons within metals. As a result, they have a short range and short penetrating distance in most materials. Beta particles, being slightly less charged, have a larger range and larger penetrating distance. Gamma rays, on the other hand, have little electric interaction with particles and travel much farther. Two diagrams below show the importance of difference in penetration. Table 22.3 shows the distance of radiation penetration, and Figure 22.21 shows the influence various factors have on radiation penetration distance.

Type of Radiation	Range
α particles	A sheet of paper, a few cm of air, fractions of a millimeter of tissue
β particles	A thin aluminum plate, tens of cm of tissue
γ rays	Several cm of lead, meters of concrete

Table 22.3 Comparing Ranges of Radioactive Decay

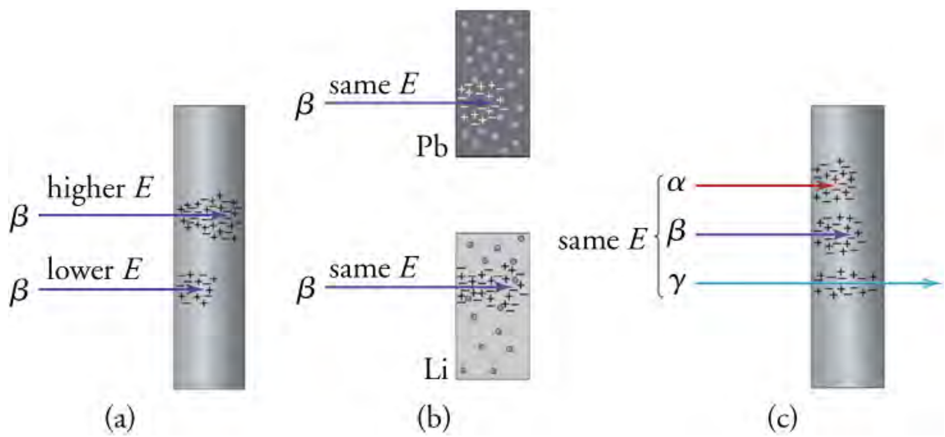


Figure 22.21 The penetration or range of radiation depends on its energy, the material it encounters, and the type of radiation. (a) Greater energy means greater range. (b) Radiation has a smaller range in materials with high electron density. (c) Alphas have the smallest range, betas have a greater range, and gammas have the greatest range.

LINKS TO PHYSICS

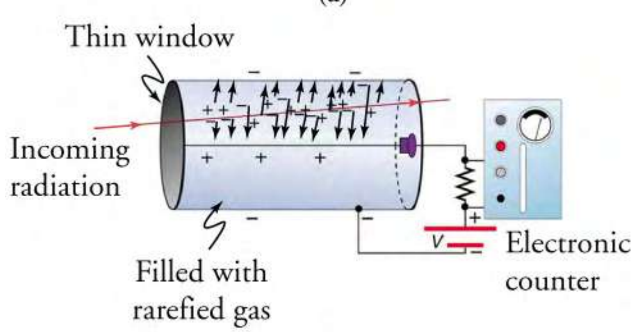
Radiation Detectors

The first direct detection of radiation was Becquerel's darkened photographic plate. Photographic film is still the most common detector of ionizing radiation, being used routinely in medical and dental X-rays. Nuclear radiation can also be captured on film, as seen in Figure 22.22. The mechanism for film exposure by radiation is similar to that by photons. A quantum of energy from a radioactive particle interacts with the emulsion and alters it chemically, thus exposing the film. Provided the radiation has more than the few eV of energy needed to induce the chemical change, the chemical alteration will occur. The amount of film darkening is related to the type of radiation and amount of exposure. The process is not 100 percent efficient, since not all incident radiation interacts and not all interactions produce the chemical change.

Figure 22.22 Film badges contain film similar to that used in this dental X-ray film. It is sandwiched between various absorbers to determine the penetrating ability of the radiation as well as the amount. Film badges are worn to determine radiation exposure. (credit: Werneuchen, Wikimedia Commons)

Another very common radiation detector is the **Geiger tube**. The clicking and buzzing sound we hear in dramatizations and documentaries, as well as in our own physics labs, is usually an audio output of events detected by a Geiger counter. These relatively inexpensive radiation detectors are based on the simple and sturdy Geiger tube, shown schematically in Figure 22.23. A conducting cylinder with a wire along its axis is filled with an insulating gas so that a voltage applied between the cylinder and wire produces almost no current. Ionizing radiation passing through the tube produces free ion pairs that are attracted to the wire and cylinder, forming a current that is detected as a count. Not every particle is detected, since some radiation can pass through without producing enough ionization. However, Geiger counters are very useful in producing a prompt output that reveals the existence and relative intensity of ionizing radiation.

(a)



(b)

Figure 22.23 (a) Geiger counters such as this one are used for prompt monitoring of radiation levels, generally giving only relative intensity and not identifying the type or energy of the radiation. (credit: Tim Vickers, Wikimedia Commons) (b) Voltage applied between the cylinder and wire in a Geiger tube affects ions and electrons produced by radiation passing through the gas-filled cylinder. Ions move toward the cylinder and electrons toward the wire. The resulting current is detected and registered as a count.

Another radiation detection method records light produced when radiation interacts with materials. The energy of the radiation is sufficient to excite atoms in a material that may fluoresce, such as the phosphor used by Rutherford's group. Materials called **scintillators** use a more complex process to convert radiation energy into light. Scintillators may be liquid or solid, and they can be very efficient. Their light output can provide information about the energy, charge, and type of radiation. Scintillator light flashes are very brief in duration, allowing the detection of a huge number of particles in short periods of time. Scintillation detectors are used in a variety of research and diagnostic applications. Among those are the detection of the radiation from distant galaxies using satellite-mounted equipment and the detection of exotic particles in accelerator laboratories.

Virtual Physics

Beta Decay

Click to view content (https://www.openstax.org/l/21betadecayvid)

Watch beta decay occur for a collection of nuclei or for an individual nucleus. With this applet, individuals or groups of students can compare half-lives!

Check Your Understanding

2. What leads scientists to infer that the nuclear strong force exists?

a. A strong force must hold all the electrons outside the nucleus of an atom.
b. A strong force must counteract the highly attractive Coulomb force in the nucleus.
c. A strong force must hold all the neutrons together inside the nucleus.
d. A strong force must counteract the highly repulsive Coulomb force between protons in the nucleus.

22.3 Half Life and Radiometric Dating

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain radioactive half-life and its role in radiometric dating
- Calculate radioactive half-life and solve problems associated with radiometric dating

Section Key Terms

activity	becquerel	carbon-14 dating
decay constant	half-life	radioactive dating

Half-Life and the Rate of Radioactive Decay

Unstable nuclei decay. However, some nuclides decay faster than others. For example, radium and polonium, discovered by Marie and Pierre Curie, decay faster than uranium. That means they have shorter lifetimes, producing a greater rate of decay. Here we will explore half-life and activity, the quantitative terms for lifetime and rate of decay.

Why do we use the term like *half-life* rather than *lifetime*? The answer can be found by examining Figure 22.24, which shows how the number of radioactive nuclei in a sample decreases with time. The time in which half of the original number of nuclei decay is defined as the **half-life**, $t_{1/2}$. After one half-life passes, half of the remaining nuclei will decay in the next half-life. Then, half of that amount in turn decays in the following half-life. Therefore, the number of radioactive nuclei decreases from N to $N/2$ in one half-life, to $N/4$ in the next, to $N/8$ in the next, and so on. Nuclear decay is an example of a purely statistical process.

TIPS FOR SUCCESS

A more precise definition of half-life is that each nucleus has a 50 percent chance of surviving for a time equal to one half-life. If an individual nucleus survives through that time, it still has a 50 percent chance of surviving through another half-life. Even if it happens to survive hundreds of half-lives, it still has a 50 percent chance of surviving through one more. Therefore, the decay of a nucleus is like random coin flipping. The chance of heads is 50 percent, no matter what has happened before. The probability concept aligns with the traditional definition of half-life. Provided the number of nuclei is reasonably large, half of the original nuclei should decay during one half-life period.

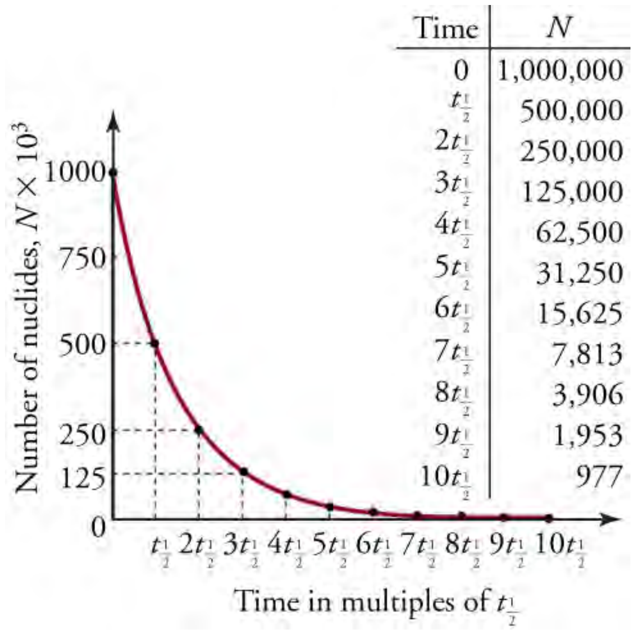


Figure 22.24 Radioactive decay reduces the number of radioactive nuclei over time. In one half-life ($t_{1/2}$), the number decreases to half of its original value. Half of what remains decays in the next half-life, and half of that in the next, and so on. This is exponential decay, as seen in the graph of the number of nuclei present as a function of time.

The following equation gives the quantitative relationship between the original number of nuclei present at time zero (N_O) and the number (N) at a later time t

$$N = N_O e^{-\lambda t}, \tag{22.45}$$

where $e = 2.71828...$ is the base of the natural logarithm, and λ is the **decay constant** for the nuclide. The shorter the half-life, the larger is the value of λ, and the faster the exponential $e^{-\lambda t}$ decreases with time. The decay constant can be found with the equation

$$\lambda = \frac{\ln(2)}{t_{1/2}} \approx \frac{0.693}{t_{1/2}}. \tag{22.46}$$

Activity, the Rate of Decay

What do we mean when we say a source is highly radioactive? Generally, it means the number of decays per unit time is very high. We define **activity** R to be the rate of decay expressed in decays per unit time. In equation form, this is

$$R = \frac{\Delta N}{\Delta t}, \tag{22.47}$$

where ΔN is the number of decays that occur in time Δt .

Activity can also be determined through the equation

$$R = \lambda N, \tag{22.48}$$

which shows that as the amount of radiative material (N) decreases, the rate of decay decreases as well.

The SI unit for activity is one decay per second and it is given the name **becquerel** (Bq) in honor of the discoverer of radioactivity. That is,

$$1 \text{ Bq} = 1 \text{ decay/second}.$$

Activity R is often expressed in other units, such as decays per minute or decays per year. One of the most common units for activity is the curie (Ci), defined to be the activity of 1 g of ^{226}Ra, in honor of Marie Curie's work with radium. The definition of the curie is

$$1 \text{ Ci} = 3.70 \times 10^{10} \text{ Bq}, \tag{22.49}$$

or 3.70×10^{10} decays per second.

Radiometric Dating

Radioactive dating or radiometric dating is a clever use of naturally occurring radioactivity. Its most familiar application is **carbon-14 dating**. Carbon-14 is an isotope of carbon that is produced when solar neutrinos strike ^{14}N particles within the atmosphere. Radioactive carbon has the same chemistry as stable carbon, and so it mixes into the biosphere, where it is consumed and becomes part of every living organism. Carbon-14 has an abundance of 1.3 parts per trillion of normal carbon, so if you know the number of carbon nuclei in an object (perhaps determined by mass and Avogadro's number), you can multiply that number by 1.3×10^{-12} to find the number of ^{14}C nuclei within the object. Over time, carbon-14 will naturally decay back to ^{14}N with a half-life of 5,730 years (note that this is an example of beta decay). When an organism dies, carbon exchange with the environment ceases, and ^{14}C is not replenished. By comparing the abundance of ^{14}C in an artifact, such as mummy wrappings, with the normal abundance in living tissue, it is possible to determine the artifact's age (or time since death). Carbon-14 dating can be used for biological tissues as old as 50 or 60 thousand years, but is most accurate for younger samples, since the abundance of ^{14}C nuclei in them is greater.

One of the most famous cases of carbon-14 dating involves the Shroud of Turin, a long piece of fabric purported to be the burial shroud of Jesus (see Figure 22.25). This relic was first displayed in Turin in 1354 and was denounced as a fraud at that time by a French bishop. Its remarkable negative imprint of an apparently crucified body resembles the then-accepted image of Jesus. As a result, the relic has been remained controversial throughout the centuries. Carbon-14 dating was not performed on the shroud until 1988, when the process had been refined to the point where only a small amount of material needed to be destroyed. Samples were tested at three independent laboratories, each being given four pieces of cloth, with only one unidentified piece from the shroud, to avoid prejudice. All three laboratories found samples of the shroud contain 92 percent of the ^{14}C found in living tissues, allowing the shroud to be dated (see Equation 22.57).

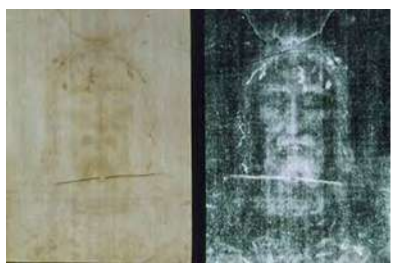


Figure 22.25 Part of the Shroud of Turin, which shows a remarkable negative imprint likeness of Jesus complete with evidence of crucifixion wounds. The shroud first surfaced in the 14th century and was only recently carbon-14 dated. It has not been determined how the image was placed on the material. (credit: Butko, Wikimedia Commons)

WORKED EXAMPLE

Carbon-11 Decay

Carbon-11 has a half-life of 20.334 min. (a) What is the decay constant for carbon-11?
If 1 kg of carbon-11 sample exists at the beginning of an hour, (b) how much material will remain at the end of the hour and (c) what will be the decay activity at that time?

Strategy

Since N_O refers to the amount of carbon-11 at the start, then after one half-life, the amount of carbon-11 remaining will be $N_O/2$. The decay constant is equivalent to the probability that a nucleus will decay each second. As a result, the half-life will need to be converted to seconds.

Solution

(a)

$$N = N_O e^{-\lambda t} \tag{22.50}$$

Since half of the carbon-11 remains after one half-life, $N/N_O = 0.5$.

$$0.5 = e^{-\lambda t} \tag{22.51}$$

Take the natural logarithm of each side to isolate the decay constant.

$$\ln(0.5) = -\lambda t \tag{22.52}$$

Convert the 20.334 min to seconds.

$$\begin{aligned} -0.693 &= (-\lambda)(20.334\ \text{min})(\tfrac{60\ \text{s}}{1\ \text{min}}) \\ -0.693 &= (-\lambda)(1{,}220.04\ \text{s}) \\ \tfrac{-0.693}{1{,}220.04\ \text{s}} &= -\lambda \\ \lambda &= 5.68\ \times\ 10^{-4}\text{s}^{-1} \end{aligned} \tag{22.53}$$

(b) The amount of material after one hour can be found by using the equation

$$N = N_O e^{-\lambda t}, \tag{22.54}$$

with t converted into seconds and N_O written as 1,000 g

$$\begin{aligned} N &= (1{,}000\ \ \text{g})e - (0.000568)(60.60) \\ N &= 129.4\ g \end{aligned} \tag{22.55}$$

(c) The decay activity after one hour can be found by using the equation

$$R = \lambda N \tag{22.56}$$

for the mass value after one hour.

$$R = \lambda N = \left(0.000568\ \frac{\text{decays}}{\text{second}}\right)(129.4\ \text{grams}) = 0.0735\ \text{Bq} \tag{22.57}$$

Discussion

(a) The decay constant shows that 0.0568 percent of the nuclei in a carbon-11 sample will decay each second. Another way of considering the decay constant is that a given carbon-11 nuclei has a 0.0568 percent probability of decaying each second. The decay of carbon-11 allows it to be used in positron emission topography (PET) scans; however, its 20.334 min half-life does pose challenges for its administration.

(b) One hour is nearly three full half-lives of the carbon-11 nucleus. As a result, one would expect the amount of sample remaining to be approximately one eighth of the original amount. The 129.4 g remaining is just a bit larger than one-eighth, which is sensible given a half-life of just over 20 min.

(c) Label analysis shows that the unit of Becquerel is sensible, as there are 0.0735 g of carbon-11 decaying each second. That is smaller amount than at the beginning of the hour, when $R = \left(0.000568\ \frac{\text{decay}}{\text{s}}\right)(1{,}000\ \text{g}) = 0.568$ g of carbon-11 were decaying each second.

WORKED EXAMPLE

How Old is the Shroud of Turin?

Calculate the age of the Shroud of Turin given that the amount of ^{14}C found in it is 92 percent of that in living tissue.

Strategy

Because 92 percent of the ^{14}C remains, $N/N_O = 0.92$. Therefore, the equation $N = N_O e^{-\lambda t}$ can be used to find λt. We also know that the half-life of ^{14}C is 5,730 years, and so once λt is known, we can find λ and then find t as requested. Here, we assume that the decrease in ^{14}C is solely due to nuclear decay.

Solution

Solving the equation $N = N_O e^{-\lambda t}$ for N/N_O gives

$$\frac{N}{N_O} = e^{-\lambda t}. \tag{22.58}$$

Thus,

$$0.92 = e^{-\lambda t}. \tag{22.59}$$

Taking the natural logarithm of both sides of the equation yields

$$\ln\ 0.92 = -\lambda t \tag{22.60}$$

so that

$$-0.0834 = -\lambda t. \tag{22.61}$$

Rearranging to isolate *t* gives

$$t = \frac{0.0834}{\lambda}. \tag{22.62}$$

Now, the equation $\lambda = \frac{0.693}{t_{1/2}}$ can be used to find λ for ^{14}C . Solving for λ and substituting the known half-life gives

$$\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{5{,}730\ \text{years}} = 1.21 \times 10^{-4}\text{y}^{-1}. \tag{22.63}$$

We enter that value into the previous equation to find t.

$$t = \frac{0.0834}{1.21 \times 10^{-4}} = 690\ \text{years}. \tag{22.64}$$

Discussion

This dates the material in the shroud to 1988–690 = 1300. Our calculation is only accurate to two digits, so that the year is rounded to 1300. The values obtained at the three independent laboratories gave a weighted average date of 1320 ± 60. That uncertainty is typical of carbon-14 dating and is due to the small amount of 14 C in living tissues, the amount of material available, and experimental uncertainties (reduced by having three independent measurements). That said, is it notable that the carbon-14 date is consistent with the first record of the shroud's existence and certainly inconsistent with the period in which Jesus lived.

There are other noncarbon forms of radioactive dating. Rocks, for example, can sometimes be dated based on the decay of ^{238}U. The decay series for ^{238}U ends with ^{206}Pb, so the ratio of those nuclides in a rock can be used an indication of how long it has been since the rock solidified. Knowledge of the ^{238}U half-life has shown, for example, that the oldest rocks on Earth solidified about 3.5×10^9 years ago.

Virtual Physics

Radioactive Dating Game

Click to view content (https://www.openstax.org/l/02radioactive_dating_game)

Learn about different types of radiometric dating, such as carbon dating. Understand how decay and half-life work to enable radiometric dating to work. Play a game that tests your ability to match the percentage of the dating element that remains to the age of the object.

22.4 Nuclear Fission and Fusion

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain nuclear fission
- Explain nuclear fusion
- Describe how the processes of fission and fusion work in nuclear weapons and in generating nuclear power

Section Key Terms

chain reaction	critical mass	liquid drop model
nuclear fission	nuclear fusion	proton-proton cycle

The previous section dealt with naturally occurring nuclear decay. Without human intervention, some nuclei will change composition in order to achieve a stable equilibrium. This section delves into a less-natural process. Knowing that energy can be emitted in various forms of nuclear change, is it possible to create a nuclear reaction through our own intervention? The answer to this question is yes. Through two distinct methods, humankind has discovered multiple ways of manipulating the atom to release its internal energy.

Nuclear Fission

In simplest terms, **nuclear fission** is the splitting of an atomic bond. Given that it requires great energy separate two nucleons, it may come as a surprise to learn that splitting a nucleus can *release* vast potential energy. And although it is true that huge amounts of energy can be released, considerable effort is needed to do so in practice.

An unstable atom will naturally decay, but it may take millions of years to do so. As a result, a physical catalyst is necessary to produce useful energy through nuclear fission. The catalyst typically occurs in the form of a free neutron, projected directly at the nucleus of a high-mass atom.

As shown in Figure 22.26, a neutron strike can cause the nucleus to elongate, much like a drop of liquid water. This is why the model is known as the **liquid drop model**. As the nucleus elongates, nucleons are no longer so tightly packed, and the repulsive electromagnetic force can overcome the short-range strong nuclear force. The imbalance of forces can result in the two ends of the drop flying apart, with some of the nuclear binding energy released to the surroundings.

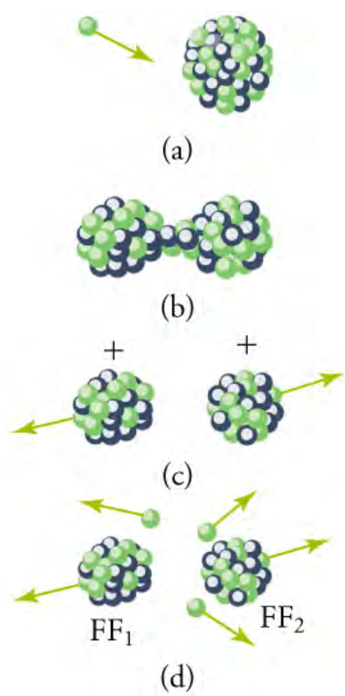


Figure 22.26 Neutron-induced fission is shown. First, energy is put into a large nucleus when it absorbs a neutron. Acting like a struck liquid drop, the nucleus deforms and begins to narrow in the middle. Since fewer nucleons are in contact, the repulsive Coulomb force is able to break the nucleus into two parts with some neutrons also flying away.

As you can imagine, the consequences of the nuclei splitting are substantial. When a nucleus is split, it is not only energy that is released, but a small number of neutrons as well. Those neutrons have the potential to cause further fission in other nuclei, especially if they are directed back toward the other nuclei by a dense shield or neutron reflector (see part (d) of Figure 22.26).

However, not every neutron produced by fission induces further fission. Some neutrons escape the fissionable material, while others interact with a nucleus without making it split. We can enhance the number of fissions produced by neutrons by having a large amount of fissionable material as well as a neutron reflector. The minimum amount necessary for self-sustained fission of a given nuclide is called its **critical mass**. Some nuclides, such as ^{239}Pu, produce more neutrons per fission than others, such as ^{235}U. Additionally, some nuclides are easier to make fission than others. In particular, ^{235}U and ^{239}Pu are easier to fission than the much more abundant ^{238}U. Both factors affect critical mass, which is smallest for ^{239}Pu. The self-sustained fission of nuclei is commonly referred to as a **chain reaction**, as shown in Figure 22.27.

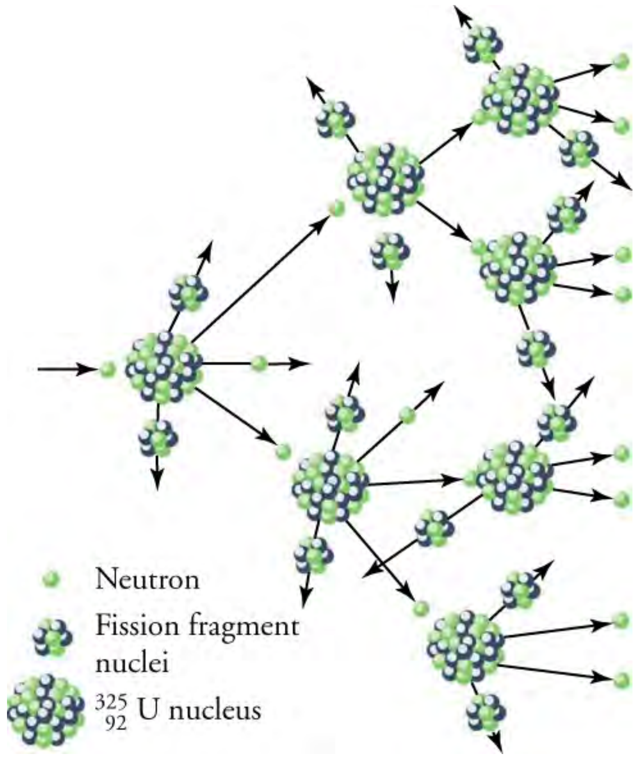


Figure 22.27 A chain reaction can produce self-sustained fission if each fission produces enough neutrons to induce at least one more fission. This depends on several factors, including how many neutrons are produced in an average fission and how easy it is to make a particular type of nuclide fission.

A chain reaction can have runaway results. If each atomic split results in two nuclei producing a new fission, the number of nuclear reactions will increase exponentially. One fission will produce two atoms, the next round of fission will create four atoms, the third round eight atoms, and so on. Of course, each time fission occurs, more energy will be emitted, further increasing the power of the atomic reaction. And that is just if two neutrons create fission reactions each round. Perhaps you can now see why so many people consider atomic energy to be an exciting energy source!

To make a self-sustained nuclear fission reactor with ^{235}U, it is necessary to slow down the neutrons. Water is very effective at this, since neutrons collide with protons in water molecules and lose energy. Figure 22.28 shows a schematic of a reactor design called the *pressurized water reactor*.

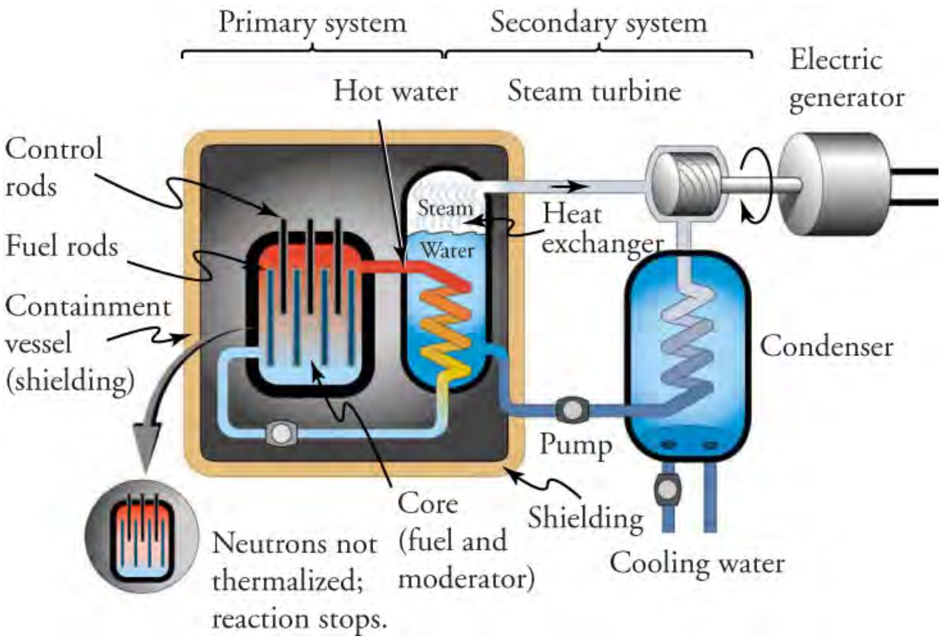


Figure 22.28 A pressurized water reactor is cleverly designed to control the fission of large amounts of ^{235}U, while using the heat produced in the fission reaction to create steam for generating electrical energy. Control rods adjust neutron flux so that it is self-sustaining. In case the reactor overheats and boils the water away, the chain reaction terminates, because water is needed to slow down the neutrons. This inherent safety feature can be overwhelmed in extreme circumstances.

Control rods containing nuclides that very strongly absorb neutrons are used to adjust neutron flux. To produce large amounts of power, reactors contain hundreds to thousands of critical masses, and the chain reaction easily becomes self-sustaining. Neutron flux must be carefully regulated to avoid an out-of-control exponential increase in the rate of fission.

Control rods help prevent overheating, perhaps even a meltdown or explosive disassembly. The water that is used to slow down neutrons, necessary to get them to induce fission in ^{235}U, and achieve criticality, provides a negative feedback for temperature increase. In case the reactor overheats and boils the water to steam or is breached, the absence of water kills the chain reaction. Considerable heat, however, can still be generated by the reactor's radioactive fission products. Other safety features, thus, need to be incorporated in the event of a loss of coolant accident, including auxiliary cooling water and pumps.

Energies in Nuclear Fission

The following are two interesting facts to consider:

- The average fission reaction produces 200 MeV of energy.
- If you were to measure the mass of the products of a nuclear reaction, you would find that their mass was slightly less than the mass of the original nucleus.

How are those things possible? Doesn't the fission reaction's production of energy violate the conservation of energy? Furthermore, doesn't the loss in mass in the reaction violate the conservation of mass? Those are important questions, and they can both be answered with one of the most famous equations in scientific history.

$$E = mc^2 \quad (22.65)$$

Recall that, according to Einstein's theory, energy and mass are essentially the same thing. In the case of fission, the mass of the products is less than that of the reactants because the missing mass appears in the form of the energy released in the reaction, with a constant value of c^2 Joules of energy converted for each kilogram of material. The value of c^2 is substantial—from Einstein's equation, the amount of energy in just 1 gram of mass would be enough to support the average U.S. citizen for more than 270 years! The example below will show you how a mass-energy transformation of this type takes place.

WORKED EXAMPLE

Calculating Energy from a Kilogram of Fissionable Fuel

Calculate the amount of energy produced by the fission of 1.00 kg of ^{235}U, given the average fission reaction of

$$^{235}\text{U produces 200 MeV.} \tag{22.66}$$

Strategy

The total energy produced is the number of ^{235}U atoms times the given energy per ^{235}U fission. We should therefore find the number of ^{235}U atoms in 1.00 kg.

Solution

The number of ^{235}U atoms in 1.00 kg is Avogadro's number times the number of moles. One mole of ^{235}U has a mass of 235.04 g; thus, there are $(1{,}000\text{ g})\,/\,(235.04.00\text{ g/mol}) = 4.25\text{ mol}$. The number of ^{235}U atoms is therefore

$$(4.25\text{ mol})\left(6.02\times10^{23}\,\text{U/mol}\right) = 2.56\times10^{24}\text{atomsof235U.}$$

So the total energy released is

$$E = \left(2.56\times10^{24}\right)\left(\frac{200\text{ MeV}}{^{235}\text{U}}\right)\left(\frac{1.60\times10^{-13}\text{J}}{\text{MeV}}\right) = 8.21\times10^{13}\,\text{J}. \tag{22.67}$$

Discussion

The result is another impressively large amount of energy, equivalent to about 14,000 barrels of crude oil or 600,000 gallons of gasoline. But, it is only one fourth the energy produced by the fusion of a kilogram of a mixture of deuterium and tritium. Even though each fission reaction yields about ten times the energy of a fusion reaction, the energy per kilogram of fission fuel is less, because there are far fewer moles per kilogram of the heavy nuclides. Fission fuel is also much scarcer than fusion fuel, and less than 1 percent of uranium (the 235 U) is readily usable.

Virtual Physics

Nuclear Fission

Click to view content (https://www.openstax.org/l/16fission)

Start a chain reaction, or introduce nonradioactive isotopes to prevent one. Use the applet to control energy production in a nuclear reactor!

Nuclear Fusion

Nuclear fusion is defined as the combining, or fusing, of two nuclei and, the combining of nuclei also results in an emission of energy. For many, the concept is counterintuitive. After all, if energy is released when a nucleus is split, how can it also be released when nucleons are combined together? The difference between fission and fusion, which results from the size of the nuclei involved, will be addressed next.

Remember that the structure of a nucleus is based on the interplay of the compressive nuclear strong force and the repulsive electromagnetic force. For nuclei that are less massive than iron, the nuclear force is actually stronger than that of the Coulomb force. As a result, when a low-mass nucleus absorbs nucleons, the added neutrons and protons bind the nucleus more tightly. The increased nuclear strong force does work on the nucleus, and energy is released.

Once the size of the created nucleus exceeds that of iron, the short-ranging nuclear force does not have the ability to bind a nucleus more tightly, and the emission of energy ceases. In fact, for fusion to occur for elements of greater mass than iron, energy must be added to the system! Figure 22.29 shows an energy-mass curve commonly used to describe nuclear reactions. Notice the location of iron (Fe) on the graph. All low-mass nuclei to the left of iron release energy through fusion, while all high-mass particles to the right of iron produce energy through fission.

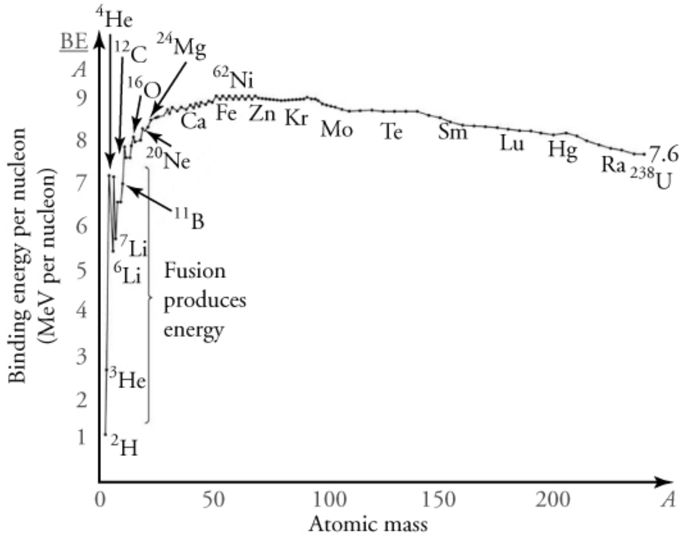


Figure 22.29 Fusion of light nuclei to form medium-mass nuclei converts mass to energy, because binding energy per nucleon (BE/A) is greater for the product nuclei. The larger BE/A is, the less mass per nucleon, and so mass is converted to energy and released in such fusion reactions.

TIPS FOR SUCCESS

Just as it is not possible for the elements to the left of iron in the figure to naturally fission, it is not possible for elements to the right of iron to naturally undergo fusion, as that process would require the addition of energy to occur. Furthermore, notice that elements commonly discussed in fission and fusion are elements that can provide the greatest change in binding energy, such as uranium and hydrogen.

Iron's location on the energy-mass curve is important, and explains a number of its characteristics, including its role as an elemental endpoint in fusion reactions in stars.

The major obstruction to fusion is the Coulomb repulsion force between nuclei. Since the attractive nuclear force that can fuse nuclei together is short ranged, the repulsion of like positive charges must be overcome in order to get nuclei close enough to induce fusion. Figure 22.30 shows an approximate graph of the potential energy between two nuclei as a function of the distance between their centers. The graph resembles a hill with a well in its center. A ball rolled to the left must have enough kinetic energy to get over the hump before it falls into the deeper well with a net gain in energy. So it is with fusion. If the nuclei are given enough kinetic energy to overcome the electric potential energy due to repulsion, then they can combine, release energy, and fall into a deep well. One way to accomplish that end is to heat fusion fuel to high temperatures so that the kinetic energy of thermal motion is sufficient to get the nuclei together.

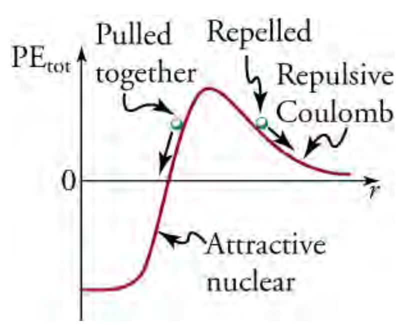


Figure 22.30 Potential energy between two light nuclei graphed as a function of distance between them. If the nuclei have enough kinetic energy to get over the Coulomb repulsion hump, they combine, release energy, and drop into a deep attractive well.

You might think that, in our Sun, nuclei are constantly coming into contact and fusing. However, this is only partially true. Only at the Sun's core are the particles close enough and the temperature high enough for fusion to occur!

In the series of reactions below, the Sun produces energy by fusing protons, or hydrogen nuclei ($^1\mathrm{H}$, by far the Sun's most abundant nuclide) into helium nuclei ^{4}He . The principal sequence of fusion reactions forms what is called the **proton-proton cycle**

$$\begin{array}{ll} ^{1}\text{H} + ^{1}\text{H} \rightarrow ^{2}\text{H} + e^{+} + v_{e} & (0.42\ \text{MeV}) \\ ^{1}\text{H} + ^{2}\text{H} \rightarrow ^{3}\text{He} + \gamma & (5.49\ \text{MeV}) \\ ^{3}\text{He} + ^{3}\text{He} \rightarrow ^{4}\text{He} + ^{1}\text{H} + ^{1}\text{H} & (12.86\ \text{MeV}), \end{array} \tag{22.68}$$

where e^{+} stands for a positron and v_e is an electron neutrino. The energy in parentheses is *released* by the reaction. Note that the first two reactions must occur twice for the third to be possible, so the cycle consumes six protons (^{1}H) but gives back two. Furthermore, the two positrons produced will find two electrons and annihilate to form four more γ rays, for a total of six. The overall cycle is thus

$$2e - +4^{1}\text{H} \rightarrow 4\ \text{He} + 2v_{e} + 6\gamma \quad (26.7\ \text{MeV}),$$

where the 26.7 MeV includes the annihilation energy of the positrons and electrons and is distributed among all the reaction products. The solar interior is dense, and the reactions occur deep in the Sun where temperatures are highest. It takes about 32,000 years for the energy to diffuse to the surface and radiate away. However, the neutrinos can carry their energy out of the Sun in less than two seconds, because they interact so weakly with other matter. Negative feedback in the Sun acts as a thermostat to regulate the overall energy output. For instance, if the interior of the Sun becomes hotter than normal, the reaction rate increases, producing energy that expands the interior. The expansion cools it and lowers the reaction rate. Conversely, if the interior becomes too cool, it contracts, increasing the temperature and therefore the reaction rate (see Figure 22.31). Stars like the Sun are stable for billions of years, until a significant fraction of their hydrogen has been depleted.

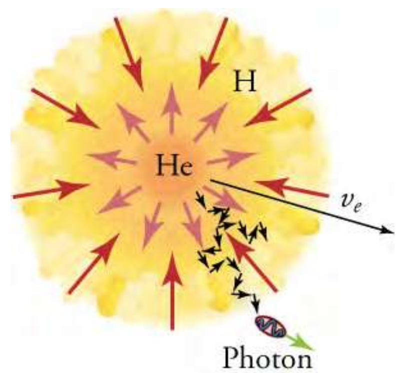


Figure 22.31 Nuclear fusion in the Sun converts hydrogen nuclei into helium; fusion occurs primarily at the boundary of the helium core, where the temperature is highest and sufficient hydrogen remains. Energy released diffuses slowly to the surface, with the exception of neutrinos, which escape immediately. Energy production remains stable because of negative-feedback effects.

Nuclear Weapons and Nuclear Power

The world was in political turmoil when fission was discovered in 1938. Compounding the troubles, the possibility of a self-sustained chain reaction was immediately recognized by leading scientists the world over. The enormous energy known to be in nuclei, but considered inaccessible, now seemed to be available on a large scale.

Within months after the announcement of the discovery of fission, Adolf Hitler banned the export of uranium from newly occupied Czechoslovakia. It seemed that the possible military value of uranium had been recognized in Nazi Germany, and that a serious effort to build a nuclear bomb had begun.

Alarmed scientists, many of whom fled Nazi Germany, decided to take action. None was more famous or revered than Einstein. It was felt that his help was needed to get the American government to make a serious effort at constructing nuclear weapons as a matter of survival. Leo Szilard, a Hungarian physicist who had emigrated to America, took a draft of a letter to Einstein, who, although a pacifist, signed the final version. The letter was for President Franklin Roosevelt, warning of the German potential to build extremely powerful bombs of a new type. It was sent in August of 1939, just before the German invasion of Poland that marked the start of World War II.

It was not until December 6, 1941, the day before the Japanese attack on Pearl Harbor, that the United States made a massive commitment to building a nuclear bomb. The top secret Manhattan Project was a crash program aimed at beating the Germans.

It was carried out in remote locations, such as Los Alamos, New Mexico, whenever possible, and eventually came to cost billions of dollars and employ the efforts of more than 100,000 people. J. Robert Oppenheimer (1904–1967), a talented physicist, was chosen to head the project. The first major step was made by Enrico Fermi and his group in December 1942, when they completed the first self-sustaining nuclear reactor. This first *atomic pile*, built in a squash court at the University of Chicago, proved that a fission chain reaction was possible.

Plutonium was recognized as easier to fission with neutrons and, hence, a superior fission material very early in the Manhattan Project. Plutonium availability was uncertain, and so a uranium bomb was developed simultaneously. Figure 22.32 shows a gun-type bomb, which takes two subcritical uranium masses and shoots them together. To get an appreciable yield, the critical mass must be held together by the explosive charges inside the cannon barrel for a few microseconds. Since the buildup of the uranium chain reaction is relatively slow, the device to bring the critical mass together can be relatively simple. Owing to the fact that the rate of spontaneous fission is low, a neutron source is at the center the assembled critical mass.

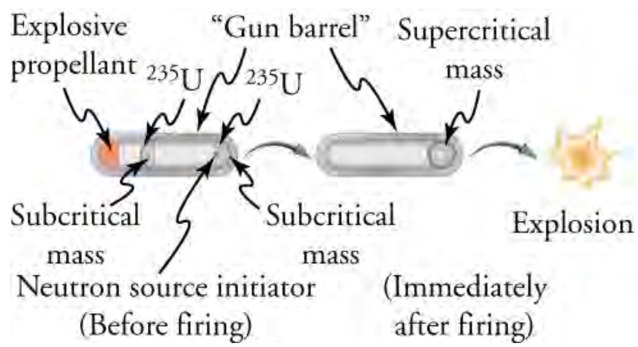


Figure 22.32 A gun-type fission bomb for ^{235}U utilizes two subcritical masses forced together by explosive charges inside a cannon barrel. The energy yield depends on the amount of uranium and the time it can be held together before it disassembles itself.

Plutonium's special properties necessitated a more sophisticated critical mass assembly, shown schematically in Figure 22.33. A spherical mass of plutonium is surrounded by shaped charges (high explosives that focus their blast) that implode the plutonium, crushing it into a smaller volume to form a critical mass. The implosion technique is faster and more effective, because it compresses three-dimensionally rather than one-dimensionally as in the gun-type bomb. Again, a neutron source is included to initiate the chain reaction.

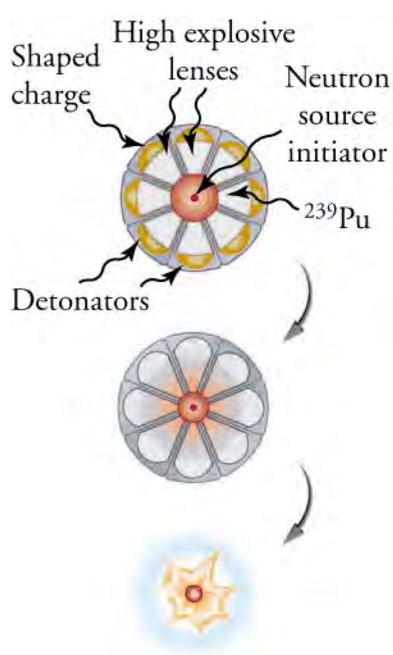


Figure 22.33 An implosion created by high explosives compresses a sphere of ^{239}Pu into a critical mass. The superior fissionability of plutonium has made it the preferred bomb material.

Owing to its complexity, the plutonium bomb needed to be tested before there could be any attempt to use it. On July 16, 1945, the test named Trinity was conducted in the isolated Alamogordo Desert in New Mexico, about 200 miles south of Los Alamos (see Figure 22.34). A new age had begun. The yield of the Trinity device was about 10 kilotons (kT), the equivalent of 5,000 of the largest conventional bombs.

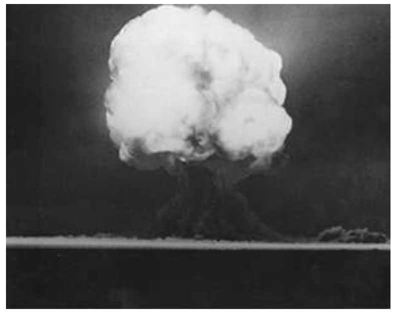


Figure 22.34 Trinity test (1945), the first nuclear bomb (credit: U.S. Department of Energy)

Although Germany surrendered on May 7, 1945, Japan had been steadfastly refusing to surrender for many months, resulting large numbers of civilian and military casualties. Invasion plans by the Allies estimated a million casualties of their own and untold losses of Japanese lives. The bomb was viewed as a way to end the war. The first bomb used was a gun-type uranium bomb dropped on Hiroshima on August 6 by the United States. Its yield of about 15 kT destroyed the city and killed an estimated 80,000 people, with 100,000 more being seriously injured. The second bomb was an implosion-type plutonium bomb dropped on Nagasaki only three days later. Its 20-kT yield killed at least 50,000 people, something less than Hiroshima because of the hilly terrain and the fact that it was a few kilometers off target. The Japanese were told that one bomb a week would be dropped until they surrendered unconditionally, which they did on August 14. In actuality, the United States had only enough plutonium for one more bomb, as yet unassembled.

Knowing that fusion produces several times more energy per kilogram of fuel than fission, some scientists pursued the idea of constructing a fusion bomb. The first such bomb was detonated by the United States several years after the first fission bombs, on October 31, 1952, at Eniwetok Atoll in the Pacific Ocean. It had a yield of 10 megatons (MT), about 670 times that of the fission bomb that destroyed Hiroshima. The Soviet Union followed with a fusion device of its own in August 1953, and a weapons race, beyond the aim of this text to discuss, continued until the end of the Cold War.

Figure 22.35 shows a simple diagram of how a thermonuclear bomb is constructed. A fission bomb is exploded next to fusion fuel in the solid form of lithium deuteride. Before the shock wave blows it apart, γ rays heat and compress the fuel, and neutrons create tritium through the reaction $n + ^6\text{Li} \rightarrow ^3\text{H} + ^4\text{He}$. Additional fusion and fission fuels are enclosed in a dense shell of ^{238}U . At the same time that the uranium shell reflects the neutrons back into the fuel to enhance its fusion, the fast-moving neutrons cause the plentiful and inexpensive ^{238}U to fission, part of what allows thermonuclear bombs to be so large.

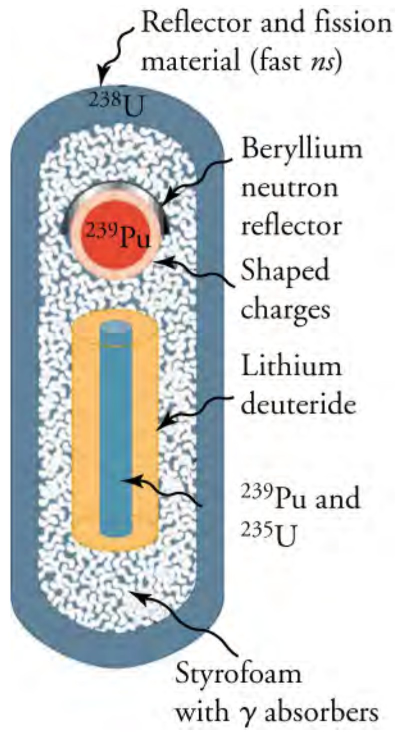


Figure 22.35 This schematic of a fusion bomb (H-bomb) gives some idea of how the $^{239}\mathrm{Pu}$ fission trigger is used to ignite fusion fuel. Neutrons and γ rays transmit energy to the fusion fuel, create tritium from deuterium, and heat and compress the fusion fuel. The outer shell of $^{238}\mathrm{U}$ serves to reflect some neutrons back into the fuel, causing more fusion, and it boosts the energy output by fissioning itself when neutron energies become high enough.

Of course, not all applications of nuclear physics are as destructive as the weapons described above. Hundreds of nuclear fission power plants around the world attest to the fact that controlled fission is both practical and economical. Given growing concerns over global warming, nuclear power is often seen as a viable alternative to energy derived from fossil fuels.

BOUNDLESS PHYSICS

Fusion Reactors

For decades, fusion reactors have been deemed the *energy of the future*. A safer, cleaner, and more abundant potential source of energy than its fission counterpart, images of the fusion reactor have been conjured up each time the need for a renewable, environmentally friendly resource is discussed. Now, after more than half a century of speculating, some scientists believe that fusion reactors are nearly here.

In creating energy by combining atomic nuclei, the fusion reaction holds many advantages over fission. First, fusion reactions are more efficient, releasing 3 to 4 times more energy than fission per gram of fuel. Furthermore, unlike fission reactions that require *heavy* elements like uranium that are difficult to obtain, fusion requires *light* elements that are abundant in nature. The greatest advantage of the fusion reaction, however, is in its ability to be controlled. While traditional nuclear reactors create worries about meltdowns and radioactive waste, neither is a substantial concern with the fusion reaction. Consider that fusion reactions require a large amount of energy to overcome the repulsive Coulomb force and that the byproducts of a fusion reaction are largely limited to helium nuclei.

In order for fusion to occur, hydrogen isotopes of deuterium and tritium must be acquired. While deuterium can easily be gathered from ocean water, tritium is slightly more difficult to come by, though it can be manufactured from Earth's abundant lithium. Once acquired, the hydrogen isotopes are injected into an empty vessel and subjected to temperature and pressure great enough to mimic the conditions at the core of our Sun. Using carefully controlled high-frequency radio waves, the hydrogen isotopes are broken into plasma and further controlled through an electromagnetic field. As the electromagnetic field continues to exert pressure on the hydrogen plasma, enough energy is supplied to cause the hydrogen plasma to fuse into helium.

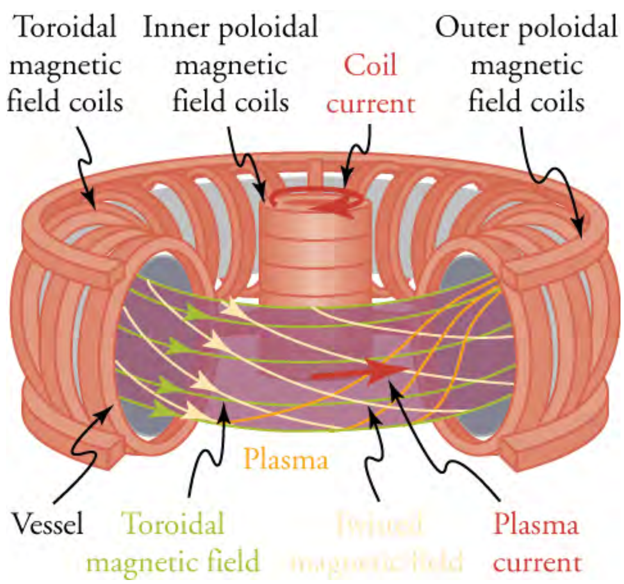


Figure 22.36 Tokamak confinement of nuclear fusion plasma. The magnetic field lines are used to confine the high-temperature plasma (purple). Research is currently being done to increase the efficiency of the tokamak confinement model.

Once the plasma fuses, high-velocity neutrons are ejected from the newly formed helium atoms. Those high velocity neutrons, carrying the excess energy stored within bonds of the original hydrogen, are able to travel unaffected by the applied magnetic field. In doing so, they strike a barrier around the nuclear reactor, transforming their excess energy to heat. The heat is then harvested to make steam that drives turbines. Hydrogen's tremendous power is now usable!

The historical concern with nuclear fusion reactors is that the energy required to control the electromagnetic field is greater than the energy harvested from the hydrogen atoms. However, recent research by both Lockheed Martin engineers and scientists at the Lawrence Livermore National Laboratory has yielded exciting theoretical improvements in efficiency. At the time of this writing, a test facility called ITER (International Thermonuclear Experimental Reactor) is being constructed in southern France. A joint venture of the European Union, the United States, Japan, Russia, China, South Korea, and India, ITER is designed for further study into the future of nuclear fusion energy production.

22.5 Medical Applications of Radioactivity: Diagnostic Imaging and Radiation

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe how nuclear imaging works (e.g., radioisotope imaging, PET)
- Describe the ionizing effects of radiation and how they can be used for medical treatment

Section Key Terms

Anger camera	rad	radiopharmaceutical	therapeutic ratio
relative biological effectiveness (RBE)	roentgen equivalent man (rem)	tagged	

Medical Applications of Nuclear Physics

Applications of nuclear physics have become an integral part of modern life. From the bone scan that detects one cancer to the radioiodine treatment that cures another, nuclear radiation has diagnostic and therapeutic effects on medicine.

Medical Imaging

A host of medical imaging techniques employ nuclear radiation. What makes nuclear radiation so useful? First, γ radiation can easily penetrate tissue; hence, it is a useful probe to monitor conditions inside the body. Second, nuclear radiation depends on the nuclide and not on the chemical compound it is in, so that a radioactive nuclide can be put into a compound designed for specific purposes. When that is done, the compound is said to be **tagged**. A tagged compound used for medical purposes is called a **radiopharmaceutical**. Radiation detectors external to the body can determine the location and concentration of a radiopharmaceutical to yield medically useful information. For example, certain drugs are concentrated in inflamed regions of the body, and their locations can aid diagnosis and treatment as seen in Figure 22.37. Another application utilizes a radiopharmaceutical that the body sends to bone cells, particularly those that are most active, to detect cancerous tumors or healing points. Images can then be produced of such bone scans. Clever use of radioisotopes determines the functioning of body organs, such as blood flow, heart muscle activity, and iodine uptake in the thyroid gland. For instance, a radioactive form of iodine can be used to monitor the thyroid, a radioactive thallium salt can be used to follow the blood stream, and radioactive gallium can be used for cancer imaging.

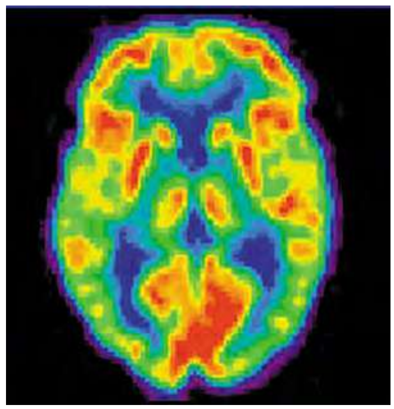


Figure 22.37 A radiopharmaceutical was used to produce this brain image of a patient with Alzheimer’s disease. Certain features are computer enhanced. (credit: National Institutes of Health)

Once a radioactive compound has been ingested, a device like that shown in Figure 22.38 is used to monitor nuclear activity. The device, called an **Anger camera** or gamma camera uses a piece of lead with holes bored through it. The gamma rays are redirected through the collimator to narrow their beam, and are then interpreted using a device called a scintillator. The computer analysis of detector signals produces an image. One of the disadvantages of this detection method is that there is no depth information (i.e., it provides a two-dimensional view of the tumor as opposed to a three-dimensional view), because radiation from any location under that detector produces a signal.

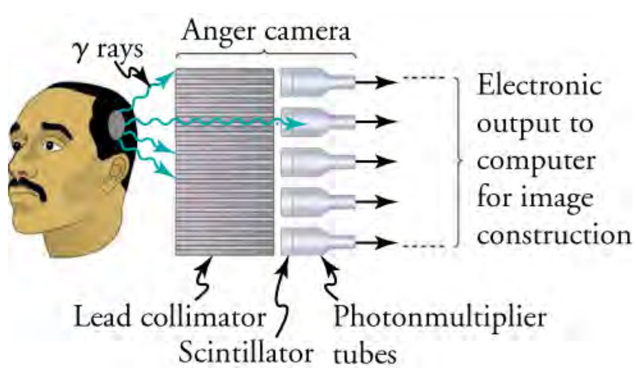


Figure 22.38 An Anger or gamma camera consists of a lead collimator and an array of detectors. Gamma rays produce light flashes in the scintillators. The light output is converted to an electrical signal by the photomultipliers. A computer constructs an image from the detector output.

Single-photon-emission computer tomography (SPECT) used in conjunction with a CT scanner improves on the process carried out by the gamma camera. Figure 22.39 shows a patient in a circular array of SPECT detectors that may be stationary or rotated, with detector output used by a computer to construct a detailed image. The spatial resolution of this technique is poor, but the three-dimensional image created results in a marked improvement in contrast.

Figure 22.39 SPECT uses a rotating camera to form an image of the concentration of a radiopharmaceutical compound. (credit: Woldo, Wikimedia Commons)

Positron emission tomography (or PET) scans utilize images produced by β^+ emitters. When the emitted positron β^+ encounters an electron, mutual annihilation occurs, producing two γ rays. Those γ rays have identical 0.511 MeV energies (the energy comes from the destruction of an electron or positron mass) and they move directly away from each other, allowing detectors to determine their point of origin accurately (as shown in Figure 22.40). It requires detectors on opposite sides to simultaneously (i.e., at the same time) detect photons of 0.511 MeV energy and utilizes computer imaging techniques similar to those in SPECT and CT scans. PET is used extensively for diagnosing brain disorders. It can note decreased metabolism in certain regions that accompany Alzheimer's disease. PET can also locate regions in the brain that become active when a person carries out specific activities, such as speaking, closing his or her eyes, and so on.

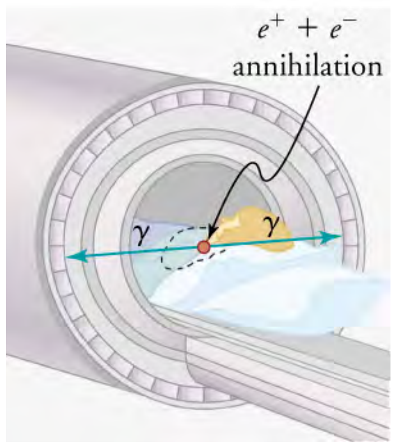


Figure 22.40 A PET system takes advantage of the two identical γ -ray photons produced by positron-electron annihilation. The γ rays are emitted in opposite directions, so that the line along which each pair is emitted is determined. Various events detected by several pairs of detectors are then analyzed by the computer to form an accurate image.

Ionizing Radiation on the Body

We hear many seemingly contradictory things about the biological effects of ionizing radiation. It can cause cancer, burns, and hair loss, and yet it is used to treat and even cure cancer. How do we understand such effects? Once again, there is an underlying simplicity in nature, even in complicated biological organisms. All the effects of ionizing radiation on biological tissue can be understood by knowing that ionizing radiation affects molecules within cells, particularly DNA molecules. Let us take a brief look at molecules within cells and how cells operate. Cells have long, double-helical DNA molecules containing chemical patterns called genetic codes that govern the function and processes undertaken by the cells. Damage to DNA consists of breaks in chemical bonds or other changes in the structural features of the DNA chain, leading to changes in the genetic code. In human cells, we can have as many as a million individual instances of damage to DNA per cell per day. The repair ability of DNA is vital for maintaining the integrity of the genetic code and for the normal functioning of the entire organism. A cell with a damaged ability to repair DNA, which could have been induced by ionizing radiation, can do one of the following:

- The cell can go into an irreversible state of dormancy, known as senescence.
- The cell can commit suicide, known as programmed cell death.
- The cell can go into unregulated cell division, leading to tumors and cancers.

Since ionizing radiation damages the DNA, ionizing radiation has its greatest effect on cells that rapidly reproduce, including most types of cancer. Thus, cancer cells are more sensitive to radiation than normal cells and can be killed by it easily. Cancer is characterized by a malfunction of cell reproduction, and can also be caused by ionizing radiation. There is no contradiction to say that ionizing radiation can be both a cure and a cause.

Radiotherapy

Radiotherapy is effective against cancer because cancer cells reproduce rapidly and, consequently, are more sensitive to radiation. The central problem in radiotherapy is to make the dose for cancer cells as high as possible while limiting the dose for normal cells. The ratio of abnormal cells killed to normal cells killed is called the **therapeutic ratio**, and all radiotherapy techniques are designed to enhance that ratio. Radiation can be concentrated in cancerous tissue by a number of techniques. One of the most prevalent techniques for well-defined tumors is a geometric technique shown in Figure 22.41. A narrow beam of radiation is passed through the patient from a variety of directions with a common crossing point in the tumor. The technique concentrates the dose in the tumor while spreading it out over a large volume of normal tissue.

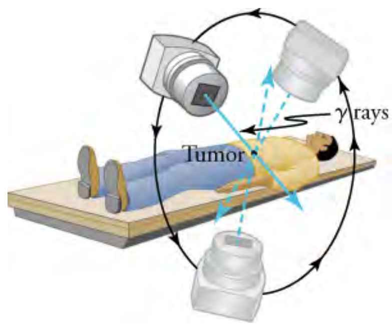


Figure 22.41 The ^{60}Co source of γ -radiation is rotated around the patient so that the common crossing point is in the tumor, concentrating the dose there. This geometric technique works for well-defined tumors.

Another use of radiation therapy is through radiopharmaceuticals. Cleverly, radiopharmaceuticals are used in cancer therapy by tagging antibodies with radioisotopes. Those antibodies are extracted from the patient, cultured, loaded with a radioisotope, and then returned to the patient. The antibodies are then concentrated almost entirely in the tissue they developed to fight, thus localizing the radiation in abnormal tissue. This method is used with radioactive iodine to fight thyroid cancer. While the therapeutic ratio can be quite high for such short-range radiation, there can be a significant dose for organs that eliminate radiopharmaceuticals from the body, such as the liver, kidneys, and bladder. As with most radiotherapy, the technique is limited by the tolerable amount of damage to the normal tissue.

Radiation Dosage

To quantitatively discuss the biological effects of ionizing radiation, we need a radiation dose unit that is directly related to those effects. To do define such a unit, it is important to consider both the biological organism and the radiation itself. Knowing that the amount of ionization is proportional to the amount of deposited energy, we define a radiation dose unit called the **rad**. It 1/100 of a joule of ionizing energy deposited per kilogram of tissue, which is

$$1 \text{ rad} = 0.01 \text{ J/kg}. \tag{22.69}$$

For example, if a 50.0-kg person is exposed to ionizing radiation over her entire body and she absorbs 1.00 J, then her whole-body radiation dose is

$$(1.00 \text{ J})/(50.0 \text{ kg}) = 0.0200 \text{ J/kg} = 2.00 \text{ rad}. \tag{22.70}$$

If the same 1.00 J of ionizing energy were absorbed in her 2.00-kg forearm alone, then the dose to the forearm would be

$$(1.00 \text{ J})/(2.00 \text{ kg}) = 0.500 \text{ J/kg} = 50.0 \text{ rad}, \tag{22.71}$$

and the unaffected tissue would have a zero rad dose. When calculating radiation doses, you divide the energy absorbed by the mass of affected tissue. You must specify the affected region, such as the whole body or forearm in addition to giving the numerical dose in rads. Although the energy per kilogram in 1 rad is small, it can still have significant effects. Since only a few eV cause ionization, just 0.01 J of ionizing energy can create a huge number of ion pairs and have an effect at the cellular level.

The effects of ionizing radiation may be directly proportional to the dose in rads, but they also depend on the type of radiation and the type of tissue. That is, for a given dose in rads, the effects depend on whether the radiation is α, β, γ, X-ray, or some other type of ionizing radiation. The **relative biological effectiveness** (RBE) relates to the amount of biological damage that can occur from a given type of radiation and is given in Table 22.4 for several types of ionizing radiation.

Type and energy of radiation	RBE
X-rays	1
γ rays	1
β rays greater than 32 keV	1
β rays less than 32 keV	1.7
Neutrons, thermal to slow (< 20 keV)	2–5
Neutrons, fast (1–10 MeV)	10 (body), 32 (eyes)
Protons (1–10 MeV)	10 (body), 32 (eyes)
α rays from radioactive decay	10–20
Heavy ions from accelerators	10–20

Table 22.4 Relative Biological Effectiveness

TIPS FOR SUCCESS

The RBEs given in Table 22.4 are approximate, but they yield certain valuable insights.

- The eyes are more sensitive to radiation, because the cells of the lens do not repair themselves.
- Though both are neutral and have large ranges, neutrons cause more damage than γ rays because neutrons often cause secondary radiation when they are captured.
- Short-range particles such as α rays have a severely damaging effect to internal anatomy, as their damage is concentrated and more difficult for the biological organism to repair. However, the skin can usually block alpha particles from entering the body.

Can you think of any other insights from the table?

A final dose unit more closely related to the effect of radiation on biological tissue is called the **roentgen equivalent man**, or rem. A combination of all factors mentioned previously, the roentgen equivalent man is defined to be the dose in rads multiplied by the relative biological effectiveness.

$$\text{rem} = \text{rad} \times \text{RBE} \tag{22.72}$$

The large-scale effects of radiation on humans can be divided into two categories: immediate effects and long-term effects. Table 22.5 gives the immediate effects of whole-body exposures received in less than one day. If the radiation exposure is spread out over more time, greater doses are needed to cause the effects listed. Any dose less than 10 rem is called a low dose, a dose 10 to 100 rem is called a moderate dose, and anything greater than 100 rem is called a high dose.

Dose (rem)	Effect
0–10	No observable effect
10–100	Slight to moderate decrease in white blood cell counts

Table 22.5 Immediate Effects of Radiation (Adults, Whole Body, Single Exposure)

Dose (rem)	Effect
50	Temporary sterility
100–200	Significant reduction in blood cell counts, brief nausea, and vomiting; rarely fatal
200–500	Nausea, vomiting, hair loss, severe blood damage, hemorrhage, fatalities
450	LD50/32; lethal to 50% of the population within 32 days after exposure if untreated
500–2,000	Worst effects due to malfunction of small intestine and blood systems; limited survival
> 2,000	Fatal within hours due to collapse of central nervous system

Table 22.5 Immediate Effects of Radiation (Adults, Whole Body, Single Exposure)

WORK IN PHYSICS

Health Physicist

Are you interested in learning more about radiation? Are you curious about studying radiation dosage levels and ensuring the safety of the environment and people that are most closely affected by it? If so, you may be interested in becoming a health physicist.

The field of health physics draws from a variety of science disciplines with the central aim of mitigating radiation concerns. Those that work as health physicists have a diverse array of potential jobs available to them, including those in research, industry, education, environmental protection, and governmental regulation. Furthermore, while the term *health physicist* may lead many to think of the medical field, there are plenty of applications within the military, industrial, and energy fields as well.

As a researcher, a health physicist can further environmental studies on the effects of radiation, design instruments for more accurate measurements, and assist in establishing valuable radiation standards. Within the energy field, a health physicsist often acts as a manager, closely tied to all operations at all levels, from procuring appropirate equipment to monitoring health data. Within industry, the health physicist acts as a consultant, assisting industry management in important decisions, designing facilities, and choosing appropriate detection tools. The health physicist possesses a unique knowledge base that allows him or her to operate in a wide variety of interesting disciplines!

To become a health physicist, it is necessary to have a background in the physical sciences. Understanding the fields of biology, physiology, biochemistry, and genetics are all important as well. The ability to analyze and solve new problems is critical, and a natural aptitude for science and mathematics will assist in the continued necessary training. There are two possible certifications for health physicists: from the American Board of Health Physicists (ABHP) and the National Registry of Radiation Protection Technologists (NRRPT).

KEY TERMS

activity rate of decay for radioactive nuclides

alpha decay type of radioactive decay in which an atomic nucleus emits an alpha particle

anger camera common medical imaging device that uses a scintillator connected to a series of photomultipliers

atomic number number of protons in a nucleus

becquerel SI unit for rate of decay of a radioactive material

beta decay type of radioactive decay in which an atomic nucleus emits a beta particle

carbon-14 dating radioactive dating technique based on the radioactivity of carbon-14

chain reaction self-sustaining sequence of events, exemplified by the self-sustaining nature of a fission reaction at critical mass

critical mass minimum amount necessary for self-sustained fission of a given nuclide

decay constant quantity that is inversely proportional to the half-life and that is used in the equation for number of nuclei as a function of time

energy-level diagram a diagram used to analyze the energy levels of electrons in the orbits of an atom

excited state any state beyond the $n = 1$ orbital in which the electron stores energy

Fraunhofer lines black lines shown on an absorption spectrum that show the wavelengths absorbed by a gas

gamma decay type of radioactive decay in which an atomic nucleus emits a gamma ray

Geiger tube very common radiation detector that usually gives an audio output

ground state the n=1 orbital of an electron

half-life time in which there is a 50 percent chance that a nucleus will decay

Heisenberg uncertainty principle fundamental limit to the precision with which pairs of quantities such as momentum and position can be measured

hydrogen-like atom any atom with only a single electron

isotope nuclei having the same Z and different N's

liquid drop model model of the atomic nucleus (useful only to understand some of its features) in which nucleons in a nucleus act like atoms in a drop

mass number number of nucleons in a nucleus

nuclear fission reaction in which a nucleus splits

nuclear fusion reaction in which two nuclei are combined, or fused, to form a larger nucleus

nucleons particles found inside nuclei

planetary model of the atom model of the atom that shows electrons orbiting like planets about a Sun-like nucleus

proton-proton cycle combined reactions $^1\text{H} + ^1\text{H} \rightarrow ^2\text{H} + e^- + v_e$, $^1\text{H} + ^2\text{H} \rightarrow ^3\text{He} + \gamma$ and $^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + ^1\text{H} + ^1\text{H}$ that begins with hydrogen and ends with helium

rad amount of ionizing energy deposited per kilogram of tissue

radioactive substance or object that emits nuclear radiation

radioactive dating application of radioactive decay in which the age of a material is determined by the amount of radioactivity of a particular type that occurs

radioactive decay process by which an atomic nucleus of an unstable atom loses mass and energy by emitting ionizing particles

radioactivity emission of rays from the nuclei of atoms

radiopharmaceutical compound used for medical imaging

relative biological effectiveness (RBE) number that expresses the relative amount of damage that a fixed amount of ionizing radiation of a given type can inflict on biological tissues

roentgen equivalent man (rem) dose unit more closely related to effects in biological tissue

Rutherford scattering scattering of alpha particles by gold nuclei in the gold foil experiment

Rydberg constant a physical constant related to atomic spectra, with an established value of $1.097 \times 10^7 \text{m}^{-1}$

scintillator radiation detection method that records light produced when radiation interacts with materials

strong nuclear force attractive force that holds nucleons together within the nucleus

tagged having a radioactive substance attached (to a chemical compound)

therapeutic ratio the ratio of abnormal cells killed to normal cells killed

transmutation process of changing elemental composition

SECTION SUMMARY

22.1 The Structure of the Atom

- Rutherford's gold foil experiment provided evidence that the atom is composed of a small, dense nucleus with electrons occupying the mostly empty space around it.
- Analysis of emission spectra shows that energy is emitted from energized gas in discrete quantities.
- The Bohr model of the atom describes electrons existing in discrete orbits, with discrete energies emitted and absorbed as the electrons decrease and increase in orbital energy.
- The energy emitted or absorbed by an electron as it changes energy state can be determined with the equation $\Delta E = E_i - E_f$, where

$E_n = \frac{Z^2}{n^2} E_o \ (n = 1, 2, 3, ...)$.

- The wavelength of energy absorbed or emitted by an electron as it changes energy state can be determined by the equation $\frac{1}{\lambda} = R\left(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2}\right)$, where $R = 1.097 \times 10^7 \mathrm{m}^{-1}$.
- Described as an electron cloud, the quantum model of the atom is the result of de Broglie waves and Heisenberg's uncertainty principle.

22.2 Nuclear Forces and Radioactivity

- The structure of the nucleus is defined by its two nucleons, the neutron and proton.
- Atomic numbers and mass numbers are used to differentiate between various atoms and isotopes. Those numbers can be combined into an easily recognizable form called a *nuclide*.
- The size and stability of the nucleus is based upon two forces: the electromagnetic force and strong nuclear force.
- Radioactive decay is the alteration of the nucleus through the emission of particles or energy.
- Alpha decay occurs when too many protons exist in the nucleus. It results in the ejection of an alpha particle, as described in the equation ${}^{A}_{Z}X_N \rightarrow {}^{A-4}_{Z-2}Y_N + {}^{4}_{2}\mathrm{He}$.
- Beta decay occurs when too many neutrons (or protons) exist in the nucleus. It results in the transmutation of a neutron into a proton, electron, and neutrino. The decay is expressed through the equation ${}^{A}_{Z}X_N \rightarrow {}_{Z+1}{}^{A}Y_{N-1} + e + v$. (Beta decay may also transform a proton into a neutron.)
- Gamma decay occurs when a nucleus in an excited state move to a more stable state, resulting in the release of a photon. Gamma decay is represented with the equation ${}^{A}_{Z}X_N \rightarrow X_N + \gamma$.
- The penetration distance of radiation depends on its energy, charge, and type of material it encounters.

22.3 Half Life and Radiometric Dating

- Radioactive half-life is the time it takes a sample of nuclei to decay to half of its original amount.
- The rate of radioactive decay is defined as the sample's activity, represented by the equation $R = \frac{\Delta N}{\Delta t}$.
- Knowing the half-life of a radioactive isotope allows for the process of radioactive dating to determine the age of a material.
- If the half-life of a material is known, the age of the material can be found using the equation $N = N_O e^{-\lambda t}$.
- The age of organic material can be determined using the decay of the carbon-14 isotope, while the age of rocks can be determined using the decay of uranium-238.

22.4 Nuclear Fission and Fusion

- Nuclear fission is the splitting of an atomic bond, releasing a large amount of potential energy previously holding the atom together. The amount of energy released can be determined through the equation $E = mc^2$.
- Nuclear fusion is the combining, or fusing together, of two nuclei. Energy is also released in nuclear fusion as the combined nuclei are closer together, resulting in a decreased strong nuclear force.
- Fission was used in two nuclear weapons at the conclusion of World War II: the gun-type uranium bomb and the implosion-type plutonium bomb.
- While fission has been used in both nuclear weapons and nuclear reactors, fusion is capable of releasing more energy per reaction. As a result, fusion is a well-researched, if not yet well-controlled, energy source.

22.5 Medical Applications of Radioactivity: Diagnostic Imaging and Radiation

- Medical imaging occurs when a radiopharmaceutical placed in the body provides information to an array of radiation detectors outside the body.
- Devices utilizing medical imaging include the Anger camera, SPECT detector, and PET scan.
- Ionizing radiation can both cure and cause cancer through the manipulation of DNA molecules.
- Radiation dosage and its effect on the body can be measured using the quantities radiation dose unit (rad), relative biological effectiveness (RBE), and the roentgen equivalent man (rem).

KEY EQUATIONS

22.1 The Structure of the Atom

energy of hydrogen electron in an orbital	$E_n = -\frac{13.6 \text{ eV}}{n^2} (n = 1, 2, 3, ...)$
energy of any hydrogen-like electron in orbital	$E_n = \frac{Z^2}{n^2} E_o \ (n = 1, 2, 3, ...)$

wavelength of light emitted by an electron changing states	$\frac{1}{\lambda} = R\left(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2}\right)$
wavelength of an orbital	$n\lambda_n = 2\pi r_n\ (n = 1, 2, 3, ...)$
heisenberg's uncertainty principle	$\Delta x \Delta p \geq \frac{h}{4\pi}$

22.2 Nuclear Forces and Radioactivity

alpha decay equation	${}^{A}_{Z}X_N \rightarrow {}^{A-4}_{Z-2}Y_N + {}^{4}_{2}\text{He}$
beta decay equation	${}^{A}_{Z}X_N \rightarrow {}_{Z+1}{}^{A}Y_{N-1} + e + v$
gamma decay equation	${}^{A}_{Z}X_N \rightarrow X_N + \gamma$

22.3 Half Life and Radiometric Dating

radioactive half-life	$N = N_O e^{-\lambda t}$

22.4 Nuclear Fission and Fusion

energy–mass conversion	$E = mc^2$
proton-proton chain	$2\text{e}- \ +\ 4{}^{1}\text{H} \ \rightarrow\ 4\ \text{He} \ +\ 2v_e \ +\ 6\gamma$

22.5 Medical Applications of Radioactivity: Diagnostic Imaging and Radiation

roentgen equivalent man	$\text{rem} = \text{rad}\ \times\ \text{RBE}$

CHAPTER REVIEW

Concept Items

22.1 The Structure of the Atom

1. A star emits light from its core. One observer views the emission unobstructed while a second observer views the emission while obstructed by a cloud of hydrogen gas. Describe the difference between their observations.
   a. Intensity of the light in the spectrum will increase.
   b. Intensity of the light in the spectrum will decrease.
   c. Frequencies will be absorbed from the spectrum.
   d. Frequencies will be added to the spectrum.

2. How does the orbital energy of a hydrogen-like atom change as it increases in atomic number?
   a. The orbital energy will increase.
   b. The orbital energy will decrease.
   c. The orbital energy will remain constant.
   d. The orbital energy will be halved.

22.4 Nuclear Fission and Fusion

3. Aside from energy yield, why are nuclear fusion reactors more desirable than nuclear fission reactors?
   a. Nuclear fusion reactors have a low installation cost.
   b. Radioactive waste is greater for a fusion reactor.
   c. Nuclear fusion reactors are easy to design and build.
   d. A fusion reactor produces less radioactive waste.

Critical Thinking Items

22.1 The Structure of the Atom

4. How would the gold foil experiment have changed if electrons were used in place of alpha particles, assuming that the electrons hit the gold foil with the same force as the alpha particles?
   a. Being less massive, the electrons might have been scattered to a greater degree than the alpha particles.
   b. Being less massive, the electrons might have been scattered to a lesser degree than the alpha particles.
   c. Being more massive, the electrons would have been scattered to a greater degree than the alpha particles.
   d. Being more massive, the electrons would have been scattered to a lesser degree than the alpha particles.

5. Why does the emission spectrum of an isolated gas differ from the emission spectrum created by a white light?
   a. White light and an emission spectrum are different varieties of continuous distribution of frequencies.
   b. White light and an emission spectrum are different series of discrete frequencies.

c. White light is a continuous distribution of frequencies, and an emission spectrum is a series of discrete frequencies.
d. White light is a series of discrete frequencies, and an emission spectrum is a continuous distribution of frequencies.

6. Why would it most likely be difficult to observe quantized orbital states for satellites orbiting the earth?
a. On a macroscopic level, the orbital states do exist for satellites orbiting Earth but are too closely spaced for us to see.
b. On a macroscopic level, the orbital states do not exist for satellites orbiting Earth.
c. On a macroscopic level, we cannot control the amount of energy that we give to an artificial satellite and thus control its orbital altitude.
d. On a macroscopic level, we cannot control the amount of energy that we give to an artificial satellite but we can control its orbital altitude.

7. Do standing waves explain why electron orbitals are quantized?
a. no
b. yes

8. Some terms referring to the observation of light include *emission spectrum* and *absorption spectrum*. Based on these definitions, what would a *reflection spectrum* describe?
a. The reflection spectrum would describe when incident waves are selectively reflected by a substance.
b. The reflection spectrum would describe when incident waves are completely reflected by a substance.
c. The reflection spectrum would describe when incident waves are not absorbed by a substance.
d. The reflection spectrum would describe when incident waves are completely absorbed by a substance.

22.2 Nuclear Forces and Radioactivity

9. Explain why an alpha particle can have a greater range in air than a beta particle in lead.
a. While the alpha particle has a lesser charge than a beta particle, the electron density in lead is much less than that in air.
b. While the alpha particle has a greater charge than a beta particle, the electron density in lead is much lower than that in air.
c. While the alpha particle has a lesser charge than a beta particle, the electron density in lead is much greater than that in air.
d. While the alpha particle has a greater charge than a beta particle, the electron density in lead is much higher than that in air.

10. What influence does the strong nuclear force have on the electrons in an atom?
a. It attracts them toward the nucleus.
b. It repels them away from the nucleus.
c. The strong force makes electrons revolve around the nucleus.
d. It does not have any influence.

22.3 Half Life and Radiometric Dating

11. Provide an example of something that decreases in a manner similar to radioactive decay.
a. The potential energy of an object falling under the influence of gravity
b. The kinetic energy of a ball that is dropped from a building to the ground
c. Theh charge transfer from an ebonite rod to fur
d. The heat transfer from a hot to a cold object

12. A sample of radioactive material has a decay constant of 0.05 s^{-1}. Why is it wrong to presume that the sample will take just 20 seconds to fully decay?
a. The decay constant varies with the mass of the sample.
b. The decay constant results vary with the amount of the sample.
c. The decay constant represents a percentage of the sample that cannot decay.
d. The decay constant represents only the fraction of a sample that decays in a unit of time, not the decay of the entire sample.

22.4 Nuclear Fission and Fusion

13. What is the atomic number of the most strongly bound nuclide?
a. 25
b. 26
c. 27
d. 28

14. Why are large electromagnets necessary in nuclear fusion reactors?
a. Electromagnets are used to slow down the movement of charge hydrogen plasma.
b. Electromagnets are used to decrease the temperature of hydrogen plasma.
c. Electromagnets are used to confine the hydrogen plasma.
d. Electromagnets are used to stabilize the temperature of the hydrogen plasma.

22.5 Medical Applications of Radioactivity: Diagnostic Imaging and Radiation

15. Why are different radiopharmaceuticals used to image different parts of the body?
- a. The different radiopharmaceuticals travel through different blood vessels.
- b. The different radiopharmaceuticals travel to different parts of the body.
- c. The different radiopharmaceuticals are used to treat different diseases of the body.
- d. The different radiopharmaceuticals produce different amounts of ionizing radiation.

16. Why do people think carefully about whether to receive a diagnostic test such as a CT scan?
- a. The radiation from a CT scan is capable of creating cancerous cells.
- b. The radiation from a CT scan is capable of destroying cancerous cells.
- c. The radiation from a CT scan is capable of creating diabetic cells.
- d. The radiation from a CT scan is capable of destroying diabetic cells.

17. Sometimes it is necessary to take a PET scan very soon after ingesting a radiopharmaceutical. Why is that the case?
- a. The radiopharmaceutical may have a short half-life.
- b. The radiopharmaceutical may have a long half-life.
- c. The radiopharmaceutical quickly passes through the digestive system.
- d. The radiopharmaceutical can become lodged in the digestive system.

Performance Task

22.5 Medical Applications of Radioactivity: Diagnostic Imaging and Radiation

18. On the Environmental Protection Agency's website, a helpful tool exists to allow you to determine your average annual radiation dose. Use the tool to determine whether the radiation level you have been exposed to is dangerous and to compare your radiation dosage to other radiative events.

1. Visit the webpage (http://www.openstax.org/l/28calculate) and answer the series of questions provided to determine the average annual radiation dosage that you receive.
2. Table 22.5 shows the immediate effects of a radiation dosage. Using the table, explain what you would experience if your yearly dosage of radiation was received all over the course of one day. Also, determine whether your dosage is considered a low, moderate, or high.
3. Using the information input into the webpage, what percentage of your dosage comes from natural sources? The average percentage of radiation from natural sources for an individual is around 85 percent.
4. Research radiation dosages for evacuees from events like the Chernobyl and Fukushima meltdowns. How does your annual radiation exposure rate compare to the net dosage for evacuees of each event. Use numbers to support your answer.
5. The U.S. Department of Labor limits the amount of radiation that a given worker may receive in a 12 month period.
   - a. Research the present maximum value and compare your annual exposure rate to that of a radiation worker. Use numbers to support your answer.
   - b. What types of work are likely to cause an increase in the radiation exposure of a particular worker?

Provide one question based upon the information gathered on the EPA website.

TEST PREP

Multiple Choice

22.1 The Structure of the Atom

19. If electrons are negatively charged and the nucleus is positively charged, why do they not attract and collide with each other?
- a. The pull from the nucleus provides a centrifugal force, which is not strong enough to draw the electrons into the nucleus.
- b. The pull from the nucleus provides a centripetal force, which is not strong enough to draw the electrons into the nucleus.

c. The pull from the nucleus provides a helical motion.
d. The pull from the nucleus provides a cycloid motion.

22.4 Nuclear Fission and Fusion

20. If a nucleus elongates due to a neutron strike, which of the following forces will decrease?
a. Nuclear force between neutrons only
b. Coulomb force between protons only
c. Strong nuclear force between all nucleons and Coulomb force between protons, but the strong force will decrease more
d. Strong nuclear force between neutrons and Coulomb force between protons, but Coulomb force will decrease more

Short Answer

22.1 The Structure of the Atom

21. Why do Bohr's calculations for electron energies not work for all atoms?
a. In atoms with more than one electron is an atomic shell, the electrons will interact. That requires a more complex formula than Bohr's calculations accounted for.
b. In atoms with 10 or more electrons in an atomic shell, the electrons will interact. That requires a more complex formula than Bohr's calculations accounted for.
c. In atoms with more than one electron in an atomic shell, the electrons will not interact. That requires a more complex formula than Bohr's calculations accounted for.
d. In atoms with 10 or more electrons in an atomic shell, the electrons will not interact. That requires a more complex formula than Bohr's calculations accounted for.

22.2 Nuclear Forces and Radioactivity

22. Does transmutation occur within chemical reactions?
a. no
b. yes

22.3 Half Life and Radiometric Dating

23. How does the radioactive activity of a sample change with time?
a. The radioactive activity decreases exponentially.
b. The radioactive activity undergoes linear decay.
c. The radioactive activity undergoes logarithmic decay.
d. The radioactive activity will not change with time.

22.4 Nuclear Fission and Fusion

24. Why does fission of heavy nuclei result in the release of neutrons?
a. Heavy nuclei require more neutrons to achieve stability.
b. Heavy nuclei require more neutrons to balance charge.
c. Light nuclei require more neutrons to achieve stability.
d. Light nuclei require more neutrons to balance charge.

22.5 Medical Applications of Radioactivity: Diagnostic Imaging and Radiation

25. Why is radioactive iodine used to monitor the thyroid?
a. Radioactive iodine can be used by the thyroid while absorbing information about the thyroid.
b. Radioactive iodine can be used by the thyroid while emitting information about the thyroid.
c. Radioactive iodine can be secreted by the thyroid while absorbing information about the thyroid.
d. Radioactive iodine can be secreted by the thyroid while emitting information about the thyroid.

Extended Response

22.1 The Structure of the Atom

26. Compare the standing wavelength of an $n = 2$ orbital to the standing wavelength of an $n = 4$ orbital.
a. The standing wavelength of an $n = 2$ orbital is greater than the standing wavelength of an $n = 4$ orbital.
b. The standing wavelength of an $n = 2$ orbital is less than the standing wavelength of an $n = 4$ orbital.
c. There is no relation between the standing wavelength of an $n = 2$ orbital and the standing wavelength of an $n = 4$ orbital.
d. The standing wavelength of an $n = 2$ orbital is the same as the standing wavelength of an$n = 4$ orbital.

27. Describe the shape of the electron cloud, based on total energy levels, for an atom with electrons in multiple orbital states.
a. There are multiple regions of high electron

probability of various shapes surrounding the nucleus.
b. There is a single solid spherical region of high electron probability surrounding the nucleus.
c. There are multiple concentric shells of high electron probability surrounding the nucleus.
d. There is a single spherical shell of high electron probability surrounding the nucleus.

22.2 Nuclear Forces and Radioactivity

28. How did Becquerel's observations of pitchblende imply the existence of radioactivity?
a. A chemical reaction occurred on the photographic plate without any external source of energy.
b. Bright spots appeared on the photographic plate due to an external source of energy.
c. Energy from the Sun was absorbed by the pitchblende and reflected onto the photographic plate.
d. Dark spots appeared on the photographic plate due to an external source of energy.

22.4 Nuclear Fission and Fusion

29. Describe the potential energy of two nuclei as they approach each other.
a. The potential energy will decrease as the nuclei are brought together and then rapidly increase once a minimum is reached.
b. The potential energy will decrease as the nuclei are brought together.
c. The potential energy will increase as the nuclei are brought together.
d. The potential energy will increase as the nuclei are brought together and then rapidly decrease once a maximum is reached.

22.5 Medical Applications of Radioactivity: Diagnostic Imaging and Radiation

30. Why do X-rays and gamma rays have equivalent RBE values if they provide different amounts of energy to the body?
a. The penetration distance, which depends on energy, is short for both X-rays and gamma rays.
b. The penetration distance, which depends on energy, is long for both X-rays and gamma rays.
c. The penetration distance, as determined by their high mass, is different for both X-rays and gamma rays.
d. The penetration distance, as determined by their low mass, is the same for both X-rays and gamma rays.

CHAPTER 23
Particle Physics

Figure 23.1 Part of the Large Hadron Collider (LHC) at CERN, on the border of Switzerland and France. The LHC is a particle accelerator, designed to study fundamental particles. (credit: Image Editor, Flickr)

Chapter Outline

23.1 The Four Fundamental Forces

23.2 Quarks

23.3 The Unification of Forces

INTRODUCTION Following ideas remarkably similar to those of the ancient Greeks, we continue to look for smaller and smaller structures in nature, hoping ultimately to find and understand the most fundamental building blocks that exist. Atomic physics deals with the smallest units of elements and compounds. In its study, we have found a relatively small number of atoms with systematic properties, and these properties have explained a tremendous range of phenomena. Nuclear physics is concerned with the nuclei of atoms and their substructures. Here, a smaller number of components—the proton and neutron—make up all nuclei. Exploring the systematic behavior of their interactions has revealed even more about matter, forces, and energy. **Particle physics** deals with the substructures of atoms and nuclei and is particularly aimed at finding those truly fundamental particles that have no further substructure. Just as in atomic and nuclear physics, we have found a complex array of particles and properties with systematic characteristics analogous to the periodic table and the chart of nuclides. An underlying structure is apparent, and there is some reason to think that we *are* finding particles that have no substructure. Of course, we have been in similar situations before. For example, atoms were once thought to be the ultimate substructures. It is possible that we could continue to find deeper and deeper structures without ever discovering the ultimate substructure—in science there is never complete certainty. See Figure 23.2.

The properties of matter are based on substructures called molecules and atoms. Each atom has the substructure of a nucleus surrounded by electrons, and their interactions explain atomic properties. Protons and neutrons—and the interactions between them—explain the stability and abundance of elements and form the substructure of nuclei. Protons and neutrons are not fundamental—they are composed of quarks. Like electrons and a few other particles, quarks may be the fundamental building blocks of all matter, lacking any further substructure. But the story is not complete because quarks and electrons may have substructures smaller than details that are presently observable.

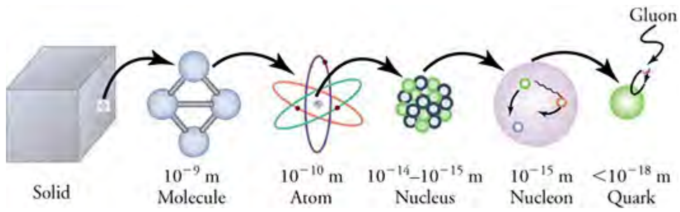


Figure 23.2 A solid, a molecule, an atom, a nucleus, a nucleon (a particle that makes up the nucleus—either a proton or a neutron), and a quark.

This chapter covers the basics of particle physics as we know it today. An amazing convergence of topics is evolving in particle physics. We find that some particles are intimately related to forces and that nature on the smallest scale may have its greatest influence on the large scale character of the universe. It is an adventure exceeding the best science fiction because it is not only fantastic but also real.

23.1 The Four Fundamental Forces

Section Learning Objectives

By the end of the section, you will be able to do the following:

- Define, describe, and differentiate the four fundamental forces
- Describe the carrier particles and explain how their exchange transmits force
- Explain how particle accelerators work to gather evidence about particle physics

Section Key Terms

carrier particle	colliding beam	cyclotron	Feynman diagram	graviton
particle physics	pion	quantum electrodynamics	synchrotron	W^- boson
W^+ boson	weak nuclear force	Z^0 boson		

Despite the apparent complexity within the universe, there remain just four basic forces. These forces are responsible for all interactions known to science: from the very small to the very large to those that we experience in our day-to-day lives. These forces describe the movement of galaxies, the chemical reactions in our laboratories, the structure within atomic nuclei, and the cause of radioactive decay. They describe the true cause behind familiar terms like friction and the normal force. These four basic forces are known as fundamental because they alone are responsible for all observations of forces in nature. The four fundamental forces are gravity, electromagnetism, **weak nuclear force**, and strong nuclear force.

Understanding the Four Forces

The gravitational force is most familiar to us because it describes so many of our common observations. It explains why a dropped ball falls to the ground and why our planet orbits the Sun. It gives us the property of weight and determines much about the motion of objects in our daily lives. Because gravitational force acts between all objects of mass and has the ability to act over large distances, the gravitational force can be used to explain much of what we observe and can even describe the motion of objects on astronomical scales! That said, gravity is incredibly weak compared to the other fundamental forces and is the weakest of all of the fundamental forces. Consider this: The entire mass of Earth is needed to hold an iron nail to the ground. Yet with a simple magnet, the force of gravity can be overcome, allowing the nail to accelerate upward through space.

The electromagnetic force is responsible for both electrostatic interactions and the magnetic force seen between bar magnets. When focusing on the electrostatic relationship between two charged particles, the electromagnetic force is known as the coulomb force. The electromagnetic force is an important force in the chemical and biological sciences, as it is responsible for molecular connections like ionic bonding and hydrogen bonding. Additionally, the electromagnetic force is behind the common physics forces of friction and the normal force. Like the gravitational force, the electromagnetic force is an inverse square law. However, the electromagnetic force does not exist between any two objects of mass, only those that are charged.

When considering the structure of an atom, the electromagnetic force is somewhat apparent. After all, the electrons are held in place by an attractive force from the nucleus. But what causes the nucleus to remain intact? After all, if all protons are positive, it makes sense that the coulomb force between the protons would repel the nucleus apart immediately. Scientists theorized that another force must exist within the nucleus to keep it together. They further theorized that this nuclear force must be significantly stronger than gravity, which has been observed and measured for centuries, and also stronger than the electromagnetic force, which would cause the protons to want to accelerate away from each other.

The strong nuclear force is an attractive force that exists between all nucleons. This force, which acts equally between proton-proton connections, proton-neutron connections, and neutron-neutron connections, is the strongest of all forces at short ranges. However, at a distance of 10^{-13} cm, or the diameter of a single proton, the force dissipates to zero. If the nucleus is large (it has many nucleons), then the distance between each nucleon could be much larger than the diameter of a single proton.

The weak nuclear force is responsible for beta decay, as seen in the equation ${}^{A}_{Z}X_N \rightarrow {}^{A}_{Z+1}Y_{N-1} + e + v$. Recall that beta decay is when a beta particle is ejected from an atom. In order to accelerate away from the nucleus, the particle must be acted on by a force. Enrico Fermi was the first to envision this type of force. While this force is appropriately labeled, it remains stronger than the gravitational force. However, its range is even smaller than that of the strong force, as can be seen in Table 23.1. The weak nuclear force is more important than it may appear at this time, as will be addressed when we discuss quarks.

Force	Approximate Relative Strength[1]	Range
Gravity	10^{-38}	∞
Weak	10^{-13}	$< 10^{-18}$ m
Electromagnetic	10^{-2}	∞
Strong	1	$< 10^{-15}$ m

[1]Relative strength is based on the strong force felt by a proton–proton pair.

Table 23.1 Relative strength and range of the four fundamental forces

Transmitting the Four Fundamental Forces

Just as it troubled Einstein prior to formulating the gravitational field theory, the concept of forces acting over a distance had greatly troubled particle physicists. That is, how does one proton *know* that another exists? Furthermore, what causes one proton to make a second proton repel? Or, for that matter, what is it about a proton that causes a neutron to attract? These mysterious interactions were first considered by Hideki Yukawa in 1935 and laid the foundation for much of what we now understand about particle physics.

Hideki Yukawa's focus was on the strong nuclear force and, in particular, its incredibly short range. His idea was a blend of particles, relativity, and quantum mechanics that was applicable to all four forces. Yukawa proposed that the nuclear force is actually transmitted by the exchange of particles, called **carrier particles**, and that what we commonly refer to as the force's field consists of these carrier particles. Specifically for the strong nuclear force, Yukawa proposed that a previously unknown particle, called a **pion**, is exchanged between nucleons, transmitting the force between them. Figure 23.3 illustrates how a pion would carry a force between a proton and a neutron.

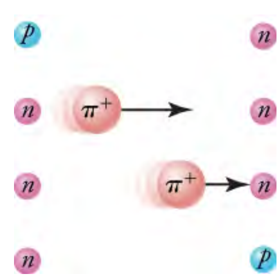


Figure 23.3 The strong nuclear force is transmitted between a proton and neutron by the creation and exchange of a pion. The pion, created through a temporary violation of conservation of mass-energy, travels from the proton to the neutron and is recaptured. It is not

directly observable and is called a virtual particle. Note that the proton and neutron change identity in the process. The range of the force is limited by the fact that the pion can exist for only the short time allowed by the Heisenberg uncertainty principle. Yukawa used the finite range of the strong nuclear force to estimate the mass of the pion; the shorter the range, the larger the mass of the carrier particle.

In Yukawa's strong force, the carrier particle is assumed to be transmitted at the speed of light and is continually transferred between the two nucleons shown. The particle that Yukawa predicted was finally discovered within cosmic rays in 1947. Its name, the pion, stands for pi meson, where meson means *medium mass*; it's a medium mass because it is smaller than a nucleon but larger than an electron. Yukawa launched the field that is now called quantum chromodynamics, and the carrier particles are now called gluons due to their strong binding power. The reason for the change in the particle name will be explained when quarks are discussed later in this section.

As you may assume, the strong force is not the only force with a carrier particle. Nuclear decay from the weak force also requires a particle transfer. In the weak force are the following three: the weak negative carrier, W^-; the weak positive carrier, W^+; and the zero charge carrier, Z^0. As we will see, Fermi inferred that these particles must carry mass, as the total mass of the products of nuclear decay is slightly larger than the total mass of all reactants after nuclear decay.

The carrier particle for the electromagnetic force is, not surprisingly, the photon. After all, just as a lightbulb can emit photons from a charged tungsten filament, the photon can be used to transfer information from one electrically charged particle to another. Finally, the **graviton** is the proposed carrier particle for gravity. While it has not yet been found, scientists are currently looking for evidence of its existence (see Boundless Physics: Searching for the Graviton).

So how does a carrier particle transmit a fundamental force? Figure 23.4 shows a virtual photon transmitted from one positively charged particle to another. The transmitted photon is referred to as a virtual particle because it cannot be directly observed while transmitting the force. Figure 23.5 shows a way of graphing the exchange of a virtual photon between the two positively charged particles. This graph of time versus position is called a **Feynman diagram**, after the brilliant American physicist Richard Feynman (1918–1988), who developed it.

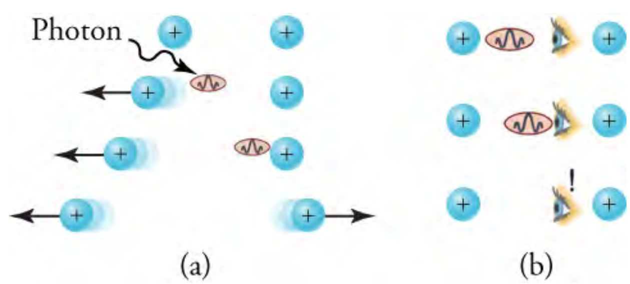


Figure 23.4 The image in part (a) shows the exchange of a virtual photon transmitting the electromagnetic force between charges, just as virtual pion exchange carries the strong nuclear force between nucleons. The image in part (b) shows that the photon cannot be directly observed in its passage because this would disrupt it and alter the force. In this case, the photon does not reach the other charge.

The Feynman diagram should be read from the bottom up to show the movement of particles over time. In it, you can see that the left proton is propelled leftward from the photon emission, while the right proton feels an impulse to the right when the photon is received. In addition to the Feynman diagram, Richard Feynman was one of the theorists who developed the field of **quantum electrodynamics** (QED), which further describes electromagnetic interactions on the submicroscopic scale. For this work, he shared the 1965 Nobel Prize with Julian Schwinger and S.I. Tomonaga. A Feynman diagram explaining the strong force interaction hypothesized by Yukawa can be seen in Figure 23.6. Here, you can see the change in particle type due to the exchange of the pi meson.

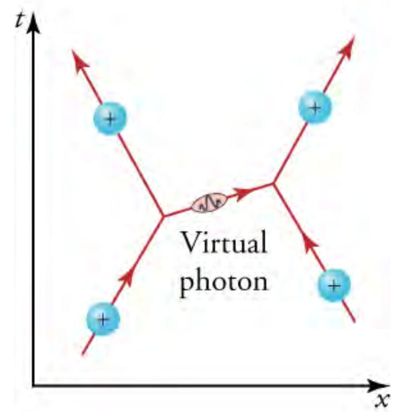


Figure 23.5 The Feynman diagram for the exchange of a virtual photon between two positively charged particles illustrates how electromagnetic force is transmitted on a quantum mechanical scale. Time is graphed vertically, while the distance is graphed horizontally. The two positively charged particles are seen to repel each other by the photon exchange.

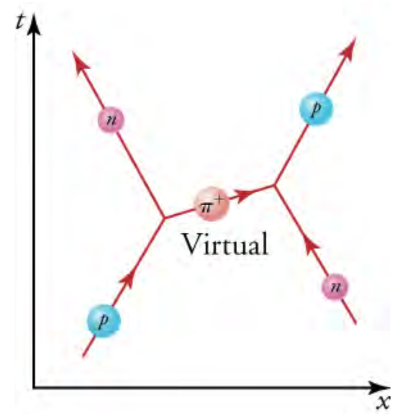


Figure 23.6 The image shows a Feynman diagram for the exchange of a π+ (pion) between a proton and a neutron, carrying the strong nuclear force between them. This diagram represents the situation shown more pictorially in Figure 23.3.

The relative masses of the listed carrier particles describe something valuable about the four fundamental forces, as can be seen in Table 23.2. **W bosons** (consisting of W^- and W^+ bosons) and **Z bosons** (Z^0 bosons), carriers of the weak nuclear force, are nearly 1,000 times more massive than pions, carriers of the strong nuclear force. Simultaneously, the distance that the weak nuclear force can be transmitted is approximately $\frac{1}{1{,}000}$ times the strong force transmission distance. Unlike carrier particles, which have a limited range, the photon is a massless particle that has no limit to the transmission distance of the electromagnetic force. This relationship leads scientists to understand that the yet-unfound graviton is likely massless as well.

Force	Carrier Particle	Range	Relative Strength[1]
Gravity	Graviton (theorized)	∞	10^{-38}
Weak	W and Z bosons	∞	10^{-2}
Electromagnetic	Photon	$< 10^{-18}$ m	10^{-13}
Strong	Pi mesons or pions (now known as gluons)	$< 10^{-15}$ m	1

[1]Relative strength is based on the strong force felt by a proton-proton pair.

Table 23.2 Carrier particles and their relative masses compared to pions for the four fundamental forces

BOUNDLESS PHYSICS

Searching for the Graviton

From Newton's Universal Law of Gravitation to Einstein's field equations, gravitation has held the focus of scientists for centuries. Given the discovery of carrier particles during the twentieth century, the importance of understanding gravitation has yet again gained the interest of prominent physicists everywhere.

With carrier particles discovered for three of the four fundamental forces, it is sensible to scientists that a similar particle, titled the **graviton**, must exist for the gravitational force. While evidence of this particle is yet to be uncovered, scientists are working diligently to discover its existence.

So what do scientists think about the unfound particle? For starters, the graviton (like the photon) should be a massless particle traveling at the speed of light. This is assumed because, like the electromagnetic force, gravity is an inverse square law, $F \approx \frac{1}{r^2}$. Scientists also theorize that the graviton is an electrically neutral particle, as an empty space within the influence of gravity is chargeless.

However, because gravity is such a weak force, searching for the graviton has resulted in some unique methods. LIGO, the Laser Interferometer Gravitational-Wave Observatory, is one tool currently being utilized (see Figure 23.7). While searching for a gravitational wave to find a carrier particle may seem counterintuitive, it is similar to the approach taken by Planck and Einstein to learn more about the photon. According to wave-particle duality, if a gravitational wave can be found, the graviton should be present along with it. Predicted by Einstein's theory of general relativity, scientists have been monitoring binary star systems for evidence of these gravitational waves.

Figure 23.7 In searching for gravitational waves, scientists are using the Laser Interferometer Gravitational-Wave Observatory (LIGO). Here we see the control room of LIGO in Hanford, Washington.

Particle accelerators like the Large Hadron Collider (LHC) are being used to search for the graviton through high-energy collisions. While scientists at the LHC speculate that the particle may not exist long enough to be seen, evidence of its prior existence, like footprints in the sand, can be found through gaps in projected energy and momentum.

Some scientists are even searching the remnants of the Big Bang in an attempt to find the graviton. By observing the cosmic background radiation, they are looking for anomalies in gravitational waves that would provide information about the gravity particles that existed at the start of our universe.

Regardless of the method used, scientists should know the graviton once they find it. A massless, chargeless particle with a spin of 2 and traveling at the speed of light—there is no other particle like it. Should it be found, its discovery would surely be considered by future generations to be on par with those of Newton and Einstein.

GRASP CHECK

Why are binary star systems used by LIGO to find gravitational waves?

a. Binary star systems have high temperature.
b. Binary star systems have low density.
c. Binary star systems contain a large amount of mass, but because they are orbiting each other, the gravitational field between the two is much less.
d. Binary star systems contain a large amount of mass. As a result, the gravitational field between the two is great.

Accelerators Create Matter From Energy

Before looking at all the particles that make up our universe, let us first examine some of the machines that create them. The fundamental process in creating unknown particles is to accelerate known particles, such as protons or electrons, and direct a beam of them toward a target. Collisions with target nuclei provide a wealth of information, such as information obtained by Rutherford in the gold foil experiment. If the energy of the incoming particles is large enough, new matter can even be created in the collision. The more energy input or ΔE, the more matter m can be created, according to mass energy equivalence $m = \Delta E/c^2$. Limitations are placed on what can occur by known conservation laws, such as conservation of mass-energy, momentum, and charge. Even more interesting are the unknown limitations provided by nature. While some expected reactions do occur, others do not, and still other unexpected reactions may appear. New laws are revealed, and the vast majority of what we know about particle physics has come from accelerator laboratories. It is the particle physicist's favorite indoor sport.

Our earliest model of a particle accelerator comes from the Van de Graaff generator. The relatively simple device, which you have likely seen in physics demonstrations, can be manipulated to produce potentials as great as 50 million volts. While these machines do not have energies large enough to produce new particles, analysis of their accelerated ions was instrumental in exploring several aspects of the nucleus.

Another equally famous early accelerator is the **cyclotron**, invented in 1930 by the American physicist, E.O. Lawrence (1901–1958). Figure 23.8 is a visual representation with more detail. Cyclotrons use fixed-frequency alternating electric fields to accelerate particles. The particles spiral outward in a magnetic field, making increasingly larger radius orbits during acceleration. This clever arrangement allows the successive addition of electric potential energy with each loop. As a result, greater particle energies are possible than in a Van de Graaff generator.

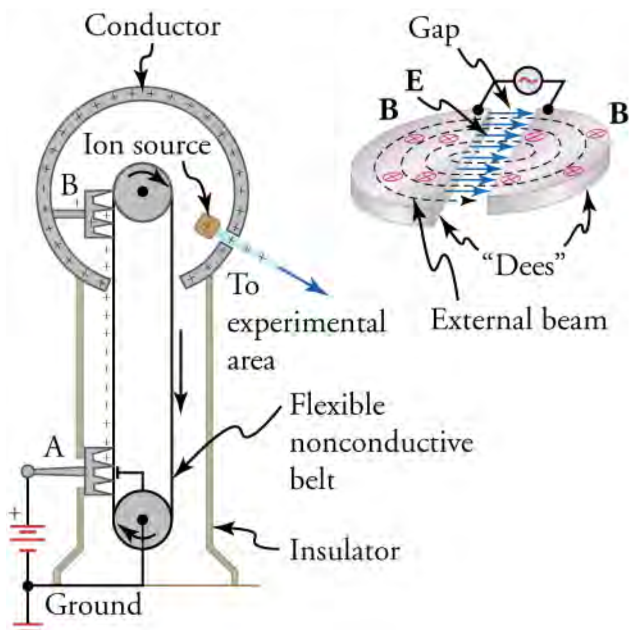


Figure 23.8 On the left is an artist's rendition of the popular physics demonstration tool, the Van de Graaff generator. A battery (A) supplies excess positive charge to a pointed conductor, the points of which spray the charge onto a moving insulating belt near the bottom. The pointed conductor (B) on top in the large sphere picks up the charge. (The induced electric field at the points is so large that it removes the charge from the belt.) This can be done because the charge does not remain inside the conducting sphere but moves to its outer surface. An ion source inside the sphere produces positive ions, which are accelerated away from the positive sphere to high velocities. On the right is a cyclotron. Cyclotrons use a magnetic field to cause particles to move in circular orbits. As the particles pass between the plates of the Dees, the voltage across the gap is oscillated to accelerate them twice in each orbit.

A **synchrotron** is a modification of the cyclotron in which particles continually travel in a fixed-radius orbit, increasing speed each time. Accelerating voltages are synchronized with the particles to accelerate them, hence the name. Additionally, magnetic field strength is increased to keep the orbital radius constant as energy increases. A ring of magnets and accelerating tubes, as shown in Figure 23.9, are the major components of synchrotrons. High-energy particles require strong magnetic fields to steer them, so superconducting magnets are commonly employed. Still limited by achievable magnetic field strengths, synchrotrons need to be very large at very high energies since the radius of a high-energy particle's orbit is very large.

To further probe the nucleus, physicists need accelerators of greater energy and detectors of shorter wavelength. To do so requires not only greater funding but greater ingenuity as well. **Colliding beams** used at both the Fermi National Accelerator Laboratory (Fermilab; see Figure 23.11) near Chicago and the LHC in Switzerland are designed to reduce energy loss in particle collisions. Typical stationary particle detectors lose a large amount of energy to the recoiling target struck by the accelerating particle. By providing head-on collisions between particles moving in opposite directions, colliding beams make it possible to create particles with momenta and kinetic energies near zero. This allows for particles of greater energy and mass to be created. Figure 23.10 is a schematic representation of this effect. In addition to circular accelerators, linear accelerators can be used to reduce energy radiation losses. The Stanford Linear Accelerator Center (now called the SLAC National Accelerator Laboratory) in California is home to the largest such accelerator in the world.

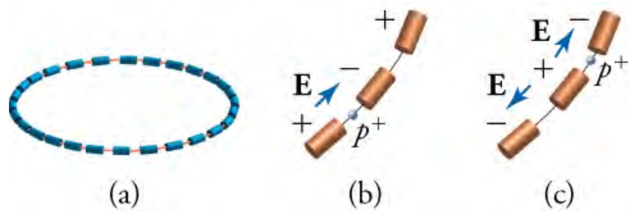


Figure 23.9 (a) A synchrotron has a ring of magnets and accelerating tubes. The frequency of the accelerating voltages is increased to cause the beam particles to travel the same distance in a shorter time. The magnetic field should also be increased to keep each beam burst traveling in a fixed-radius path. Limits on magnetic field strength require these machines to be very large in order to accelerate particles to very high energies. (b) A positively charged particle is shown in the gap between accelerating tubes. (c) While the particle passes through the tube, the potentials are reversed so that there is another acceleration at the next gap. The frequency of the reversals needs to be varied as the particle is accelerated to achieve successive accelerations in each gap.

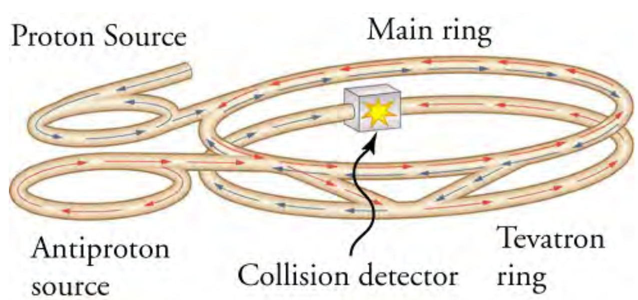


Figure 23.10 This schematic shows the two rings of Fermilab's accelerator and the scheme for colliding protons and antiprotons (not to scale).

Figure 23.11 The Fermi National Accelerator Laboratory, near Batavia, Illinois, was a subatomic particle collider that accelerated protons and antiprotons to attain energies up to 1 Tev (a trillion electronvolts). The circular ponds near the rings were built to dissipate waste heat. This accelerator was shut down in September 2011. (credit: Fermilab, Reidar Hahn)

Check Your Understanding

1. Which of the four forces is responsible for radioactive decay?

a. the electromagnetic force

b. the gravitational force
c. the strong nuclear force
d. the weak nuclear force

2. What force or forces exist between an electron and a proton?
   a. the strong nuclear force, the electromagnetic force, and gravity
   b. the weak nuclear force, the strong nuclear force, and gravity
   c. the weak nuclear force, the strong nuclear force, and the electromagnetic force
   d. the weak nuclear force, the electromagnetic force, and gravity

3. What is the proposed carrier particle for the gravitational force?
   a. boson
   b. graviton
   c. gluon
   d. photon

4. What is the relationship between the mass and range of a carrier particle?
   a. Range of a carrier particle is inversely proportional to its mass.
   b. Range of a carrier particle is inversely proportional to square of its mass.
   c. Range of a carrier particle is directly proportional to its mass.
   d. Range of a carrier particle is directly proportional to square of its mass.

5. What type of particle accelerator uses fixed-frequency oscillating electric fields to accelerate particles?
   a. cyclotron
   b. synchrotron
   c. betatron
   d. Van de Graaff accelerator

6. How does the expanding radius of the cyclotron provide evidence of particle acceleration?
   a. A constant magnetic force is exerted on particles at all radii. As the radius increases, the velocity of the particle must increase to maintain this constant force.
   b. A constant centripetal force is exerted on particles at all radii. As the radius increases, the velocity of the particle must decrease to maintain this constant force.
   c. A constant magnetic force is exerted on particles at all radii. As the radius increases, the velocity of the particle must decrease to maintain this constant force.
   d. A constant centripetal force is exerted on particles at all radii. As the radius increases, the velocity of the particle must increase to maintain this constant force.

7. Which of the four forces is responsible for the structure of galaxies?
   a. electromagnetic force
   b. gravity
   c. strong nuclear force
   d. weak nuclear force

23.2 Quarks

Section Learning Objectives

By the end of the section, you will be able to do the following:

- Describe quarks and their relationship to other particles
- Distinguish hadrons from leptons
- Distinguish matter from antimatter
- Describe the standard model of the atom
- Define a Higgs boson and its importance to particle physics

Section Key Terms

annihilation	antimatter	baryon	bottom quark	charmed quark
color	down quark	flavor	gluon	hadron
Higgs boson	Higgs field	lepton	meson	pair production
positron	quantum chromodynamics	quark	Standard Model	strange quark
top quark	up quark			

Quarks

"The first principles of the universe are atoms and empty space. Everything else is merely thought to exist…"

"… Further, the atoms are unlimited in size and number, and they are borne along with the whole universe in a vortex, and thereby generate all composite things—fire, water, air, earth. For even these are conglomerations of given atoms. And it because of their solidity that these atoms are impassive and unalterable."

—Diogenes Laertius (summarizing the views of Democritus, circa 460–370 B.C.)

The search for fundamental particles is nothing new. Atomists of the Greek and Indian empires, like Democritus of fifth century B.C., openly wondered about the most finite components of our universe. Though dormant for centuries, curiosity about the atomic nature of matter was reinvigorated by Rutherford's gold foil experiment and the discovery of the nucleus. By the early 1930s, scientists believed they had fully determined the tiniest constituents of matter—in the form of the proton, neutron, and electron.

This would be only partially true. At present, scientists know that there are hundreds of particles not unlike our electron and nucleons, all making up what some have termed the *particle zoo*. While we are confident that the electron remains fundamental, it is surrounded by a plethora of similar sounding terms, like leptons, hadrons, baryons, and mesons. Even though not every particle is considered fundamental, they all play a vital role in understanding the intricate structure of our universe.

A fundamental particle is defined as a particle with no substructure and no finite size. According to the **Standard Model**, there are three types of fundamental particles: leptons, quarks, and carrier particles. As you may recall, carrier particles are responsible for transmitting fundamental forces between their interacting masses. **Leptons** are a group of six particles not bound by the strong nuclear force, of which the electron is one. As for quarks, they are the fundamental building blocks of a group of particles called **hadrons**, a group that includes both the proton and the neutron.

Now for a brief history of **quarks**. Quarks were first proposed independently by American physicists Murray Gell-Mann and George Zweig in 1963. Originally, three quark types—or **flavors**—were proposed with the names **up** (u), **down** (d), and **strange** (s).

At first, physicists expected that, with sufficient energy, we should be able to free quarks and observe them directly. However, this has not proved possible, as the current understanding is that the force holding quarks together is incredibly great and, much like a spring, increases in magnitude as the quarks are separated. As a result, when large energies are put into collisions, other particles are created—but no quarks emerge. With that in mind, there is compelling evidence for the existence of quarks. By 1967, experiments at the SLAC National Accelerator Laboratory scattering 20-GeV electrons from protons produced results like Rutherford had obtained for the nucleus nearly 60 years earlier. The SLAC scattering experiments showed unambiguously that there were three point-like (meaning they had sizes considerably smaller than the probe's wavelength) charges inside the proton as seen in Figure 23.12. This evidence made all but the most skeptical admit that there was validity to the quark substructure of hadrons.

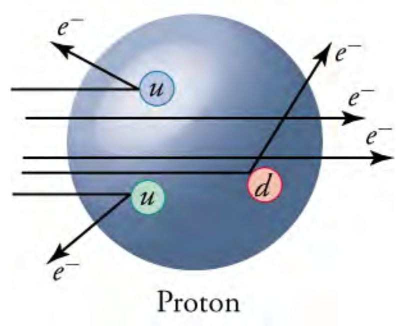


Figure 23.12 Scattering of high-energy electrons from protons at facilities like SLAC produces evidence of three point-like charges consistent with proposed quark properties. This experiment is analogous to Rutherford's discovery of the small size of the nucleus by scattering α particles. High-energy electrons are used so that the probe wavelength is small enough to see details smaller than the proton.

The inclusion of the strange quark with Zweig and Gell-Mann's model concerned physicists. While the up and down quarks demonstrated fairly clear symmetry and were present in common fundamental particles like protons and neutrons, the strange quark did not have a counterpart of its own. This thought, coupled with the four known leptons at the time, caused scientists to predict that a fourth quark, yet to be found, also existed.

In 1974, two groups of physicists independently discovered a particle with this new quark, labeled **charmed**. This completed the second *exotic* quark pair, strange (s) and charmed (c). A final pair of quarks was proposed when a third pair of leptons was discovered in 1975. The existence of the **bottom** (b) quark and the **top** (t) quark was verified through experimentation in 1976 and 1995, respectively. While it may seem odd that so much time would elapse between the original quark discovery in 1967 and the verification of the top quark in 1995, keep in mind that each quark discovered had a progressively larger mass. As a result, each new quark has required more energy to discover.

TIPS FOR SUCCESS

Note that a very important tenet of science occurred throughout the period of quark discovery. The charmed, bottom, and top quarks were all speculated on, and then were discovered some time later. Each of their discoveries helped to verify and strengthen the quark model. This process of speculation and verification continues to take place today and is part of what drives physicists to search for evidence of the graviton and Grand Unified Theory.

One of the most confounding traits of quarks is their electric charge. Long assumed to be discrete, and specifically a multiple of the elementary charge of the electron, the electric charge of an individual quark is fractional and thus seems to violate a presumed tenet of particle physics. The fractional charge of quarks, which are $\pm\left(\frac{2}{3}\right)q_e$ and $\pm\left(\frac{1}{3}\right)q_e$, are the only structures found in nature with a nonintegral number of charge q . However, note that despite this odd construction, the fractional value of the quark does not violate the quantum nature of the charge. After all, free quarks cannot be found in nature, and all quarks are bound into arrangements in which an integer number of charge is constructed. Table 23.3 shows the six known quarks, in addition to their antiquark components, as will be discussed later in this section.

Flavor	Symbol	Antiparticle	Charge[1][2]
Up	u	$\overline{u}$	$\pm\frac{2}{3}q_e$
Down	d	$\overline{d}$	$\mp\frac{1}{3}q_e$
Strange	s	$\overline{s}$	$\mp\frac{1}{3}q_e$
Charmed	c	$\overline{c}$	$\pm\frac{2}{3}q_e$

[1]The lower of the $\pm$ symbols are the values for antiquarks.
[2]There are further qualities that differentiate between quarks. However, they are beyond the discussion in this text.

Table 23.3 Quarks and Antiquarks

Flavor	Symbol	Antiparticle	Charge[1][2]
Bottom	b	$\overline{b}$	$\mp\frac{1}{3}q_e$
Top	t	$\overline{t}$	$\pm\frac{2}{3}q_e$

[1]The lower of the $\pm$ symbols are the values for antiquarks.

[2]There are further qualities that differentiate between quarks. However, they are beyond the discussion in this text.

Table 23.3 Quarks and Antiquarks

While the term *flavor* is used to differentiate between types of quarks, the concept of **color** is more analogous to the electric charge in that it is primarily responsible for the force interactions between quarks. Note—Take a moment to think about the electrostatic force. It is the electric charge that causes attraction and repulsion. It is the same case here but with a *color* charge. The three colors available to a quark are red, green, and blue, with antiquarks having colors of anti-red (or cyan), anti-green (or magenta), and anti-blue (or yellow).

Why use colors when discussing quarks? After all, the quarks are not actually colored with visible light. The reason colors are used is because the properties of a quark are analogous to the three primary and secondary colors mentioned above. Just as different colors of light can be combined to create white, different *colors* of quark may be combined to construct a particle like a proton or neutron. In fact, for each hadron, the quarks must combine such that their color sums to white! Recall that two up quarks and one down quark construct a proton, as seen in Figure 23.12. The sum of the three quarks' colors—red, green, and blue—yields the color white. This theory of color interaction within particles is called **quantum chromodynamics**, or QCD. As part of QCD, the strong nuclear force can be explained using color. In fact, some scientists refer to the color force, not the strong force, as one of the four fundamental forces. Figure 23.13 is a Feynman diagram showing the interaction between two quarks by using the transmission of a colored **gluon**. Note that the gluon is also considered the charge carrier for the strong nuclear force.

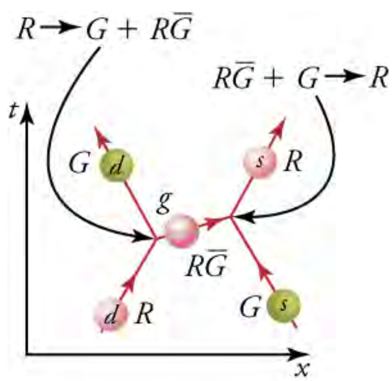


Figure 23.13 The exchange of gluons between quarks carries the strong force and may change the color of the interacting quarks. While the colors of the individual quarks change, their flavors do not.

Note that quark flavor may have any color. For instance, in Figure 23.13, the down quark has a red color and a green color. In other words, colors are not specific to a particle quark flavor.

Hadrons and Leptons

Particles can be revealingly grouped according to what forces they feel between them. All particles (even those that are massless) are affected by gravity since gravity affects the space and time in which particles exist. All charged particles are affected by the electromagnetic force, as are neutral particles that have an internal distribution of charge (such as the neutron with its magnetic moment). Special names are given to particles that feel the strong and weak nuclear forces. Hadrons are particles that feel the strong nuclear force, whereas leptons are particles that do not. All particles feel the weak nuclear force. This means that hadrons are distinguished by being able to feel both the strong and weak nuclear forces. Leptons and hadrons are distinguished in other ways as well. Leptons are fundamental particles that have no measurable size, while hadrons are composed of quarks and have a diameter on the order of 10 to 15 m. Six particles, including the electron and neutrino, make up the list of known leptons. There are hundreds of complex particles in the hadron class, a few of which (including the proton and neutron) are listed in Table 23.4.

Category	Particle Name	Symbol	Antiparticle	Rest Mass $\left(\mathrm{MeV}/c^2\right)$	Mean Lifetime (s)
Leptons	Electron	e^-	e^+	0.511	Stable
	Neutrino (e)	ν_e	$\overline{\nu}_e$	$0\ (7.0\,\mathrm{eV})$ [1]	Stable
	Muon	μ^-	μ^+	105.7	2.20×10^{-6}
	Neutrino (μ)	ν_μ	$\overline{\nu}_\mu$	$0\ (<0.27)$ [1]	Stable
	Tau	τ^-	τ^+	1,777	2.91×10^{-6}
	Neutrino (τ)	ν_τ	$\overline{\nu}_\tau$	$0\ (<31)$ [1]	Stable
Hadrons – Mesons[2]	Pion	π^+	π^-	139.6	2.60×10^{-8}
		π^0	Self	135.0	8.40×10^{-17}
	Kaon	K^+	K^-	493.7	1.24×10^{-8}
		K^0	K^0	497.6	0.90×10^{-10}
	Eta	η^0	Self	547.9	2.53×10^{-19}
Hadrons – Baryons[3]	Proton	p	$\overline{p}$	938.3	Stable
	Neutron	n	$\overline{n}$	939.6	882
	Lambda	Λ^0	$\overline{\Lambda}^0$	1,115.7	2.63×10^{-10}
	Omega	Ω^-	Ω^+	1,672.5	0.82×10^{-10}

[1]Neutrino masses may be zero. Experimental upper limits are given in parentheses.
[2]Many other mesons known
[3]Many other baryons known

Table 23.4 List of Leptons and Hadrons.

There are many more leptons, mesons, and baryons yet to be discovered and measured. The purpose of trying to uncover the smallest indivisible things in existence is to explain the world around us through forces and the interactions between particles, galaxies and objects. This is why a handful of scientists devote their life's work to smashing together small particles.

What internal structure makes a proton so different from an electron? The proton, like all hadrons, is made up of quarks. A few examples of hadron quark composition can be seen in Figure 23.14. As shown, each hadron is constructed of multiple quarks. As mentioned previously, the fractional quark charge in all four hadrons sums to the particle's integral value. Also, notice that the color composition for each of the four particles adds to white. Each of the particles shown is constructed of up, down, and their antiquarks. This is not surprising, as the quarks strange, charmed, top, and bottom are found in only our most exotic particles.

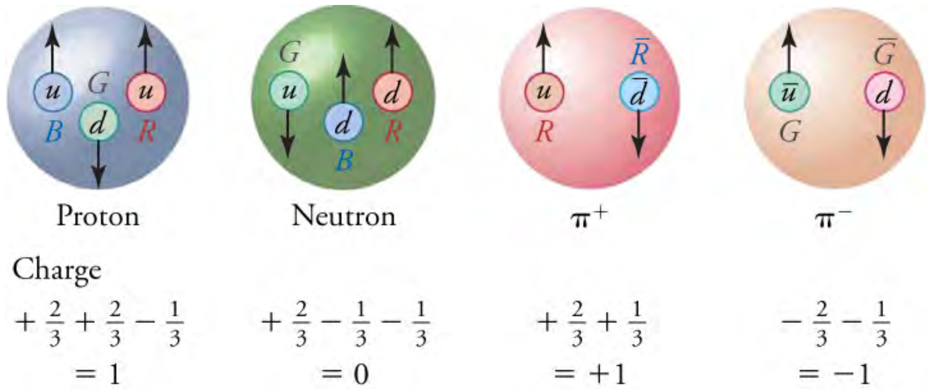


Figure 23.14 All baryons, such as the proton and neutron shown here, are composed of three quarks. All mesons, such as the pions shown here, are composed of a quark–antiquark pair. Arrows represent the spins of the quarks. The colors are such that they need to add to white for any possible combination of quarks.

You may have noticed that while the proton and neutron in Figure 23.14 are composed of three quarks, both pions are comprised of only two quarks. This refers to a final delineation in particle structure. Particles with three quarks are called **baryons**. These are heavy particles that can decay into another baryon. Particles with only two quarks—a-quark–anti-quark pair—are called **mesons**. These are particles of moderate mass that cannot decay into the more massive baryons.

Before continuing, take a moment to view Figure 23.15. In this figure, you can see the strong force reimagined as a color force. The particles interacting in this figure are the proton and neutron, just as they were in Figure 23.6. This reenvisioning of the strong force as an interaction between colored quarks is the critical concept behind quantum chromodynamics.

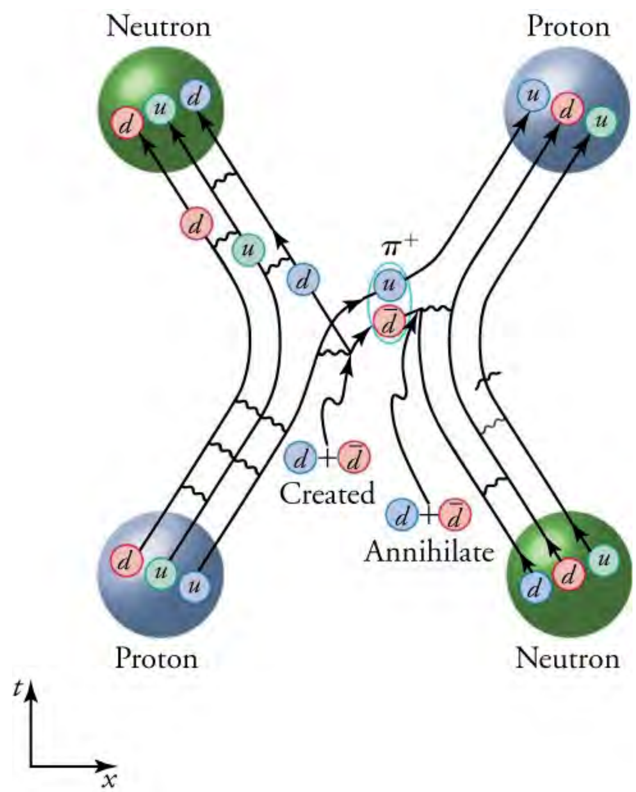


Figure 23.15 This Feynman diagram shows the interaction between a proton and a neutron, corresponding to the interaction shown in Figure 23.6. This diagram, however, shows the quark and gluon details of the strong nuclear force interaction.

Matter and Antimatter

Antimatter was first discovered in the form of the **positron**, the positively charged electron. In 1932, American physicist Carl Anderson discovered the positron in cosmic ray studies. Through a cloud chamber modified to curve the trajectories of cosmic rays, Anderson noticed that the curves of some particles followed that of a negative charge, while others curved like a positive charge. However, the positive curve showed not the mass of a proton but the mass of an electron. This outcome is shown in Figure 23.16 and suggests the existence of a positively charged version of the electron, created by the destruction of solar photons.

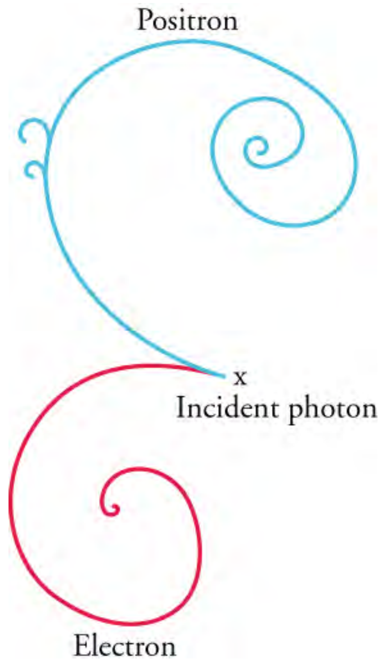


Figure 23.16 The image above is from the Fermilab *15 foot bubble chamber* and shows the production of an electron and positron (or antielectron) from an incident photon. This event is titled **pair production** and provides evidence of antimatter, as the two repel each other.

Antimatter is considered the opposite of matter. For most antiparticles, this means that they share the same properties as their original particles with the exception of their charge. This is why the positron can be considered a positive electron while the antiproton is considered a negative proton. The idea of an opposite charge for neutral particles (like the neutron) can be confusing, but it makes sense when considered from the quark perspective. Just as the neutron is composed of one up quark and two down quarks (of charge $+\frac{2}{3}$ and $-\frac{1}{3}$, respectively), the antineutron is composed of one anti–up quark and two anti–down quarks (of charge $-\frac{2}{3}$ and $+\frac{1}{3}$, respectively). While the overall charge of the neutron remains the same, its constituent particles do not!

A word about antiparticles: Like regular particles, antiparticles could function just fine on their own. In fact, a universe made up of antimatter may operate just as our own matter-based universe does. However, we do not know fully whether this is the case. The reason for this is **annihilation**. Annihilation is the process of destruction that occurs when a particle and its antiparticle interact. As soon as two particles (like a positron and an electron) coincide, they convert their masses to energy through the equation $E = mc^2$. This mass-to-energy conversion, which typically results in photon release, happens instantaneously and makes it very difficult for scientists to study antimatter. That said, scientists have had success creating antimatter through high-energy particle collisions. Both antineutrons and antiprotons were created through accelerator experiments in 1956, and an anti–hydrogen atom was even created at CERN in 1995! As referenced in , the annihilation of antiparticles is currently used in medical studies to determine the location of radioisotopes.

Completing the Standard Model of the Atom

The Standard Model of the atom refers to the current scientific view of the fundamental components and interacting forces of matter. The Standard Model (Figure 23.17) shows the six quarks that bind to form all hadrons, the six lepton particles already considered fundamental, the four carrier particles (or gauge bosons) that transmit forces between the leptons and quarks, and the recently added **Higgs boson** (which will be discussed shortly). This totals 17 fundamental particles, combinations of which are responsible for all known matter in our entire universe! When adding the antiquarks and antileptons, 31 components make up the Standard Model.

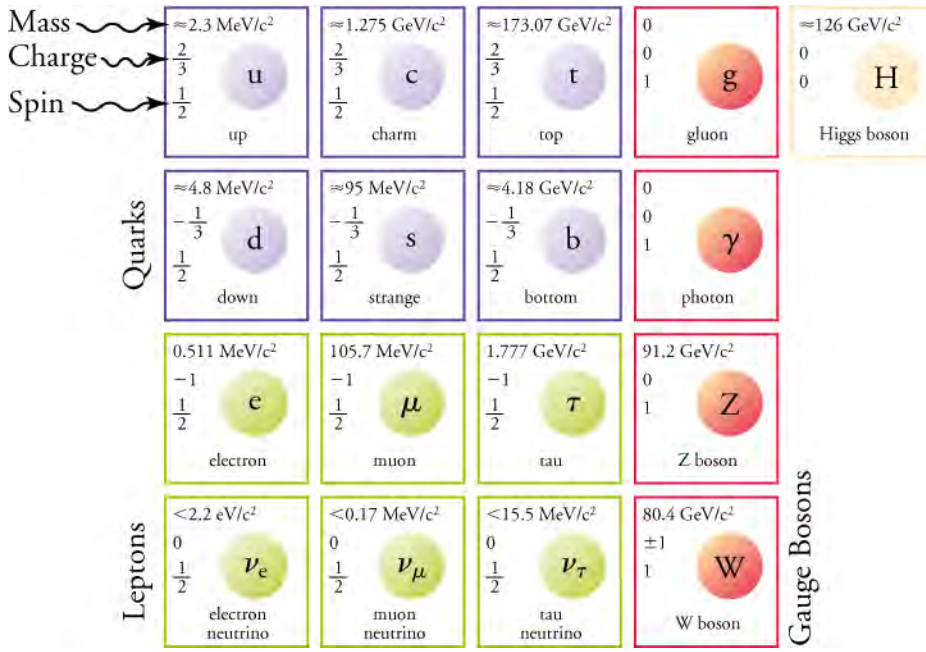


Figure 23.17 The Standard Model of elementary particles shows an organized view of all fundamental particles, as currently known: six quarks, six leptons, and four gauge bosons (or carrier particles). The Higgs boson, first observed in 2012, is a new addition to the Standard Model.

Figure 23.17 shows all particles within the Standard Model of the atom. Not only does this chart divide all known particles by color-coded group, but it also provides information on particle stability. Note that the color-coding system in this chart is separate from the red, green, and blue color labeling system of quarks. The first three columns represent the three *families* of matter. The first column, considered Family 1, represents particles that make up normal matter, constructing the protons, neutrons, and electrons that make up the common world. Family 2, represented from the charm quark to the muon neutrino, is comprised of particles that are more massive. The leptons in this group are less stable and more likely to decay. Family 3, represented by the third column, are more massive still and decay more quickly. The order of these families also conveniently represents the order in which these particles were discovered.

TIPS FOR SUCCESS

Look for trends that exist within the Standard Model. Compare the charge of each particle. Compare the spin. How does mass relate to the model structure? Recognizing each of these trends and asking questions will yield more insight into the organization of particles and the forces that dictate particle relationships. Our understanding of the Standard Model is still young, and the questions you may have in analyzing the Standard Model may be some of the same questions that particle physicists are searching for answers to today!

The Standard Model also summarizes the fundamental forces that exist as particles interact. A closer look at the Standard Model, as shown in Figure 23.18, reveals that the arrangement of carrier particles describes these interactions.

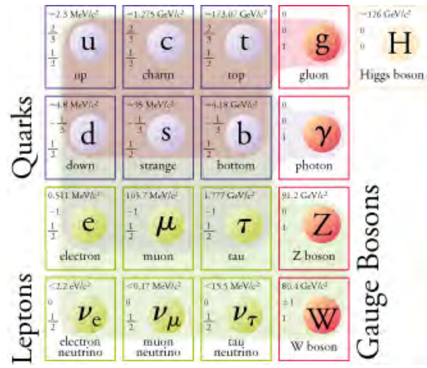


Figure 23.18 The revised Standard Model shows the interaction between gauge bosons and other fundamental particles. These interactions are responsible for the fundamental forces, three of which are described through the chart's shaded areas.

Each of the shaded areas represents a fundamental force and its constituent particles. The red shaded area shows all particles involved in the strong nuclear force, which we now know is due to quantum chromodynamics. The blue shaded area corresponds to the electromagnetic force, while the green shaded area corresponds to the weak nuclear force, which affects all quarks and leptons. The electromagnetic force and weak nuclear force are considered united by the electroweak force within the Standard Model. Also, because definitive evidence of the graviton is yet to be found, it is not included in the Standard Model.

The Higgs Boson

One interesting feature of the Standard Model shown in Figure 23.18 is that, while the gluon and photon have no mass, the Z and W bosons are very massive. What supplies these quickly moving particles with mass and not the gluons and photons? Furthermore, what causes some quarks to have more mass than others?

In the 1960s, British physicist Peter Higgs and others speculated that the W and Z bosons were actually just as massless as the gluon and photon. However, as the W and Z bosons traveled from one particle to another, they were slowed down by the presence of a **Higgs field**, much like a fish swimming through water. The thinking was that the existence of the Higgs field would slow down the bosons, causing them to decrease in energy and thereby transfer this energy to mass. Under this theory, all particles pass through the Higgs field, which exists throughout the universe. The gluon and photon travel through this field as well but are able to do so unaffected.

The presence of a force from the Higgs field suggests the existence of its own carrier particle, the Higgs boson. This theorized boson interacts with all particles but gluons and photons, transferring force from the Higgs field. Particles with large mass (like the top quark) are more likely to receive force from the Higgs boson.

While it is difficult to examine a field, it is somewhat simpler to find evidence of its carrier. On July 4, 2012, two groups of scientists at the LHC independently confirmed the existence of a Higgs-like particle. By examining trillions of proton–proton collisions at energies of 7 to 8 TeV, LHC scientists were able to determine the constituent particles that created the protons. In this data, scientists found a particle with similar mass, spin, parity, and interactions with other particles that matched the Higgs boson predicted decades prior. On March 13, 2013, the existence of the Higgs boson was tentatively confirmed by CERN. Peter Higgs and Francois Englert received the Nobel Prize in 2013 for the "theoretical discovery of a mechanism that contributes to our understanding of the origin and mass of subatomic particles."

WORK IN PHYSICS

Particle Physicist

If you have an innate desire to unravel life's great mysteries and further understand the nature of the physical world, a career in particle physics may be for you!

Particle physicists have played a critical role in much of society's technological progress. From lasers to computers, televisions to space missions, splitting the atom to understanding the DNA molecule to MRIs and PET scans, much of our modern society is based on the work done by particle physicists.

While many particle physicists focus on specialized tasks in the fields of astronomy and medicine, the main goal of particle physics is to further scientists' understanding of the Standard Model. This may mean work in government, industry, or academics. Within the government, jobs in particle physics can be found within the National Institute for Standards and Technology, Department of Energy, NASA, and Department of Defense. Both the electronics and computer industries rely on the expertise of particle physicists. College teaching and research positions can also be potential career opportunities for particle physicists, though they often require some postgraduate work as a prerequisite. In addition, many particle physicists are employed to work on high-energy colliders. Domestic collider labs include the Brookhaven National Laboratory in New York, the Fermi National Accelerator Laboratory near Chicago, and the SLAC National Accelerator Laboratory operated by Stanford University. For those who like to travel, work at international collider labs can be found at the CERN facility in Switzerland in addition to institutes like the Budker Institute of Nuclear Physics in Russia, DESY in Germany, and KEK in Japan.

Shirley Jackson became the first African American woman to earn a Ph.D. from MIT back in 1973, and she went on to lead a highly successful career in the field of particle physics. Like Dr. Jackson, successful students of particle physics grow up with a strong curiosity in the world around them and a drive to continually learn more. If you are interested in exploring a career in particle physics, work to achieve good grades and SAT scores, and find time to read popular books on physics topics that interest you. While some math may be challenging, recognize that this is only a tool of physics and should not be considered prohibitive to the field. High-level work in particle physics often requires a Ph.D.; however, it is possible to find work with a master's degree. Additionally, jobs in industry and teaching can be achieved with solely an undergraduate degree.

GRASP CHECK

What is the primary goal of all work in particle physics?

a. The primary goal is to further our understanding of the Standard Model.
b. The primary goal is to further our understanding of Rutherford's model.
c. The primary goal is to further our understanding of Bohr's model.
d. The primary goal is to further our understanding of Thomson's model.

Check Your Understanding

8. In what particle were quarks originally discovered?

a. the electron
b. the neutron
c. the proton
d. the photon

9. Why was the existence of the charm quark speculated, even though no direct evidence of it existed?

a. The existence of the charm quark was symmetrical with up and down quarks. Additionally, there were two known leptons at the time and only two quarks.
b. The strange particle lacked the symmetry that existed with the up and down quarks. Additionally, there were four known leptons at the time and only three quarks.
c. The bottom particle lacked the symmetry that existed with the up and down quarks. Additionally, there were two known leptons at the time and only two quarks.
d. The existence of charm quarks was symmetrical with up and down quarks. Additionally, there were four known leptons at the time and only three quarks.

10. What type of particle is the electron?

a. The electron is a lepton.
b. The electron is a hadron.
c. The electron is a baryon.
d. The electron is an antibaryon.

11. How do the number of fundamental particles differ between hadrons and leptons?

a. Hadrons are constructed of at least three fundamental quark particles, while leptons are fundamental particles.
b. Hadrons are constructed of at least three fundamental quark particles, while leptons are constructed of two fundamental particles.
c. Hadrons are constructed of at least two fundamental quark particles, while leptons are constructed of three

fundamental particles.
d. Hadrons are constructed of at least two fundamental quark particles, while leptons are fundamental particles.

12. Does antimatter exist?
a. no
b. yes

13. How does the deconstruction of a photon into an electron and a positron uphold the principles of mass and charge conservation?
a. The sum of the masses of an electron and a positron is equal to the mass of the photon before pair production. The sum of the charges on an electron and a positron is equal to the zero charge of the photon.
b. The sum of the masses of an electron and a positron is equal to the mass of the photon before pair production. The sum of the same charges on an electron and a positron is equal to the charge on a photon.
c. During the particle production the total energy of the photon is converted to the mass of an electron and a positron. The sum of the opposite charges on the electron and positron is equal to the zero charge of the photon.
d. During particle production, the total energy of the photon is converted to the mass of an electron and a positron. The sum of the same charges on an electron and a positron is equal to the charge on a photon.

14. How many fundamental particles exist in the Standard Model, including the Higgs boson and the graviton (not yet observed)?
a. 12
b. 15
c. 13
d. 19

15. Why do gluons interact only with particles in the first two rows of the Standard Model?
a. The leptons in the third and fourth rows do not have mass, but the gluons can interact between the quarks through gravity only.
b. The leptons in the third and fourth rows do not have color, but the gluons can interact between quarks through color interactions only.
c. The leptons in the third and fourth rows do not have spin, but the gluons can interact between quarks through spin interactions only.
d. The leptons in the third and fourth rows do not have charge, but the gluons can interact between quarks through charge interactions only.

16. What fundamental property is provided by particle interaction with the Higgs boson?
a. charge
b. mass
c. spin
d. color

17. Considering the Higgs field, what differentiates more massive particles from less massive particles?
a. More massive particles interact more with the Higgs field than the less massive particles.
b. More massive particles interact less with the Higgs field than the less massive particles.

18. What particles were launched into the proton during the original discovery of the quark?
a. bosons
b. electrons
c. neutrons
d. photons

23.3 The Unification of Forces

Section Learning Objectives

By the end of the section, you will be able to do the following:

- Define a grand unified theory and its importance
- Explain the evolution of the four fundamental forces from the Big Bang onward
- Explain how grand unification theories can be tested

Section Key Terms

Big Bang	Electroweak Epoch	electroweak theory	Grand Unification Epoch	Grand Unified Theory
Inflationary Epoch	Planck Epoch	Quark Era	superforce	Theory of Everything

Understanding the Grand Unified Theory

Present quests to show that the four basic forces are different manifestations of a single unified force that follow a long tradition. In the nineteenth century, the distinct electric and magnetic forces were shown to be intimately connected and are now collectively called the electromagnetic force. More recently, the weak nuclear force was united with the electromagnetic force. As shown in Figure 23.19, carrier particles transmit three of the four fundamental forces in very similar ways. With these considerations in mind, it is natural to suggest that a theory may be constructed in which the strong nuclear, weak nuclear, and electromagnetic forces are all unified. The search for a correct theory linking the forces, called the **Grand Unified Theory (GUT)**, is explored in this section.

In the 1960s, the **electroweak theory** was developed by Steven Weinberg, Sheldon Glashow, and Abdus Salam. This theory proposed that the electromagnetic and weak nuclear forces are identical at sufficiently high energies. At lower energies, like those in our present-day universe, the two forces remain united but manifest themselves in different ways. One of the main consequences of the electroweak theory was the prediction of three short-range carrier particles, now known as the W^+, W^-, and Z^0 bosons. Not only were three particles predicted, but the mass of each W^+ and W^- boson was predicted to be 81 GeV/c^2, and that of the Z^0 boson was predicted to be 90 GeV/c^2. In 1983, these carrier particles were observed at CERN with the predicted characteristics, including masses having those predicted values as given in .

How can forces be unified? They are definitely distinct under most circumstances. For example, they are carried by different particles and have greatly different strengths. But experiments show that at extremely short distances and at extremely high energies, the strengths of the forces begin to become more similar, as seen in Figure 23.20.

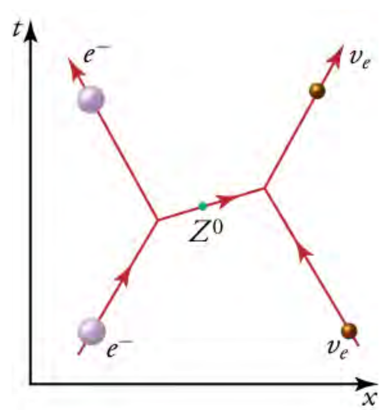


Figure 23.19 The exchange of a virtual Z^0 particle (boson) carries the weak nuclear force between an electron and a neutrino in this Feynman diagram. This diagram is similar to the diagrams in Figure 23.6 and for the electromagnetic and strong nuclear forces.

As discussed earlier, the short ranges and large masses of the weak carrier bosons require correspondingly high energies to create them. Thus, the energy scale on the horizontal axis of Figure 23.20 also corresponds to shorter and shorter distances (going from left to right), with 100 GeV corresponding to approximately 10^{-18} m, for example. At that distance, the strengths of the electromagnetic and weak nuclear forces are the same. To test this, energies of about 100 GeV are put into the system. When this occurs, the W^+, W^-, and Z^0 carrier particles are created and released. At those and higher energies, the masses of the carrier particles become less and less relevant, and the Z^0 boson in particular resembles the massless, chargeless photon. As further energy is added, the W^+, W^-, and Z^0 particles are further transformed into massless carrier particles even more similar to photons and gluons.

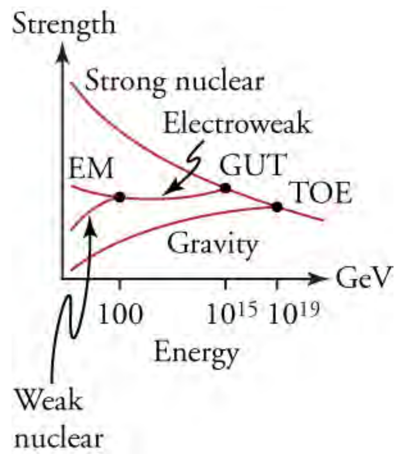


Figure 23.20 The relative strengths of the four basic forces vary with distance, and, hence, energy is needed to probe small distances. At ordinary energies (a few eV or less), the forces differ greatly. However, at energies available in accelerators, the weak nuclear and electromagnetic (EM) forces become unified. Unfortunately, the energies at which the strong nuclear and electroweak forces become the same are unreachable in any conceivable accelerator. The universe may provide a laboratory, and nature may show effects at ordinary energies that give us clues about the validity of this graph.

The extremely short distances and high energies at which the electroweak force becomes identical with the strong nuclear force are not reachable with any conceivable human-built accelerator. At energies of about 10^{14} GeV (16,000 J per particle), distances of about 10 to 30 m can be probed. Such energies are needed to test the theory directly, but these are about 10^{10} times higher than the maximum energy associated with the LHC, and the distances are about 10 to 12 smaller than any structure we have direct knowledge of. This would be the realm of various GUTs, of which there are many, since there is no constraining evidence at these energies and distances. Past experience has shown that anytime you probe so many orders of magnitude further, you find the unexpected.

While direct evidence of a GUT is not presently possible, that does not rule out the ability to assess a GUT through an indirect process. Current GUTs require various other events as a consequence of their theory. Some GUTs require the existence of magnetic monopoles, very massive individual north- and south-pole particles, which have not yet been proven to exist, while others require the use of extra dimensions. However, not all theories result in the same consequences. For example, disproving the existence of magnetic monopoles will not disprove all GUTs. Much of the science we accept in our everyday lives is based on different models, each with their own strengths and limitations. Although a particular model may have drawbacks, that does not necessarily mean that it should be discounted completely.

One consequence of GUTs that can theoretically be assessed is proton decay. Multiple current GUTs hypothesize that the stable proton should actually decay at a lifetime of 10^{31} years. While this time is incredibly large (keep in mind that the age of the universe is less than 14 billion years), scientists at the Super-Kamiokande in Japan have used a 50,000-ton tank of water to search for its existence. The decay of a single proton in the Super-Kamiokande tank would be observed by a detector, thereby providing support for the predicting GUT model. However, as of 2014, 17 years into the experiment, decay is yet to be found. This time span equates to a minimum limit on proton life of 5.9×10^{33} years. While this result certainly does not support many grand unifying theories, an acceptable model may still exist.

TIPS FOR SUCCESS

The Super-Kamiokande experiment is a clever use of proportional reasoning. Because it is not feasible to test for 10^{31} years in order for a single proton to decay, scientists chose instead to manipulate the proton–time ratio. If one proton decays in 10^{31}

years, then in one year 10^{-31} protons will decay. With this in mind, if scientists wanted to test the proton decay theory in one year, they would need 10^{31} protons. While this is also unfeasible, the use of a 50,000-ton tank of water helps to bring both the wait time and proton number to within reason.

The Standard Model and the Big Bang

Nature is full of examples where the macroscopic and microscopic worlds intertwine. Newton realized that the nature of gravity on Earth that pulls an apple to the ground could explain the motion of the moon and planets so much farther away. Decays of tiny nuclei explain the hot interior of the Earth. Fusion of nuclei likewise explains the energy of stars. Today, the patterns in particle physics seem to be explaining the evolution and character of the universe. And the nature of the universe has implications for unexplored regions of particle physics.

In 1929, Edwin Hubble observed that all but the closest galaxies surrounding our own had a red shift in their hydrogen spectra that was proportional to their distance from us. Applying the Doppler Effect, Hubble recognized that this meant that all galaxies were receding from our own, with those farther away receding even faster. Knowing that our place in the universe was no more unique than any other, the implication was clear: The space within the universe itself was expanding. Just like pen marks on an expanding balloon, everything in the universe was accelerating away from everything else.

Figure 23.21 shows how the recession of galaxies looks like the remnants of a gigantic explosion, the famous **Big Bang**. Extrapolating backward in time, the Big Bang would have occurred between 13 and 15 billion years ago, when all matter would have been at a single point. From this, questions instantly arise. What caused the explosion? What happened before the Big Bang? Was there a before, or did time start then? For our purposes, the biggest question relating to the Big Bang is this: How does the Big Bang relate to the unification of the fundamental forces?

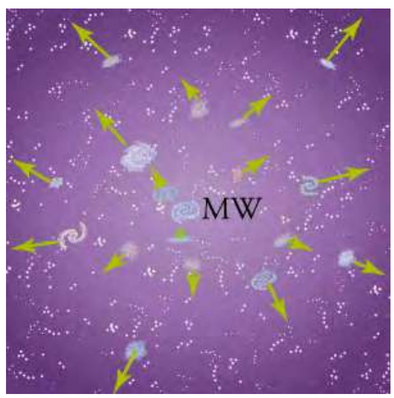


Figure 23.21 Galaxies are flying apart from one another, with the more distant ones moving faster, as if a primordial explosion expelled the matter from which they formed. The most distant known galaxies move nearly at the speed of light relative to us.

To fully understand the conditions of the very early universe, recognize that as the universe contracts to the size of the Big Bang, changes will occur. The density and temperature of the universe will increase dramatically. As particles become closer together, they will become too close to exist as we know them. The high energies will create other, more unusual particles to exist in greater abundance. Knowing this, let's move forward from the start of the universe, beginning with the Big Bang, as illustrated in Figure 23.22.

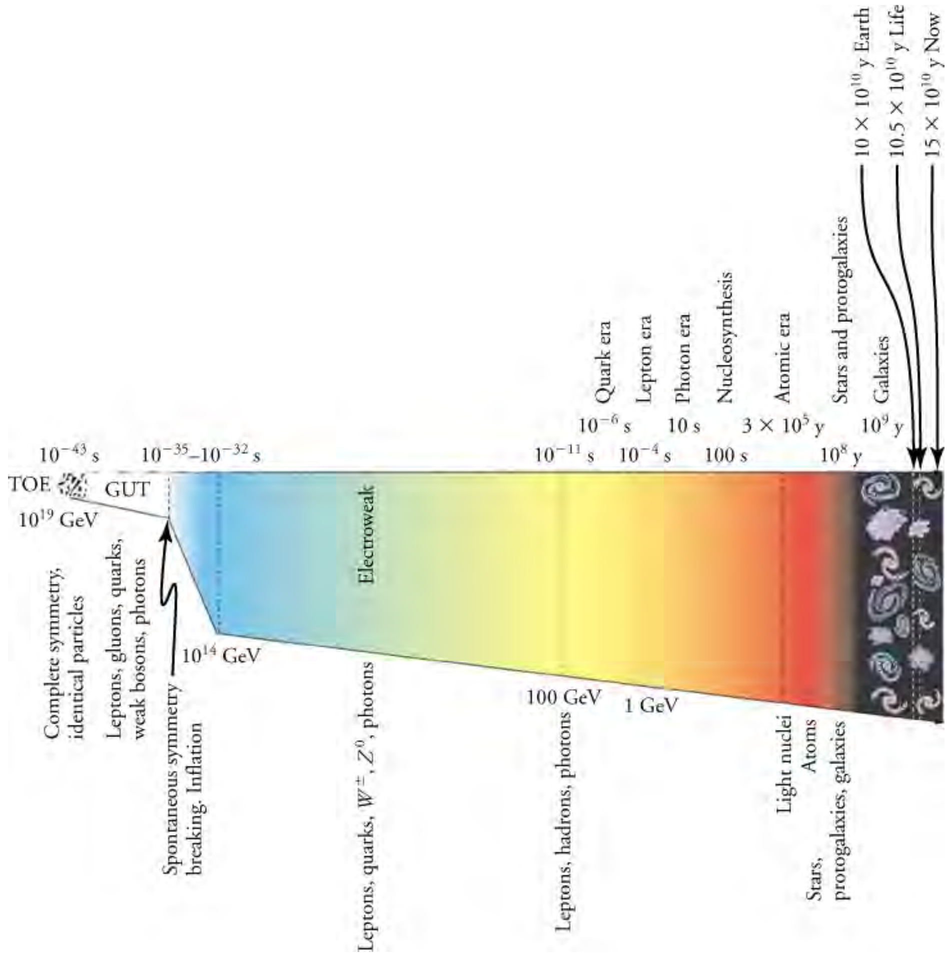


Figure 23.22 The evolution of the universe from the Big Bang onward (from left to right) is intimately tied to the laws of physics, especially those of particle physics at the earliest stages. Theories of the unification of forces at high energies may be verified by their shaping of the universe and its evolution.

The **Planck Epoch** $\left(0 \rightarrow 10^{-43}\ \text{s}\right)$—Though scientists are unable to model the conditions of the Planck Epoch in the laboratory, speculation is that at this time compressed energy was great enough to reach the immense 10^{19} GeV necessary to unify gravity with all other forces. As a result, modern cosmology suggests that all four forces would have existed as one force, a hypothetical **superforce** as suggested by the **Theory of Everything**.

The **Grand Unification Epoch** $\left(10^{-43} \rightarrow 10^{-36}\ \text{s}\right)$—As the universe expands, the temperatures necessary to maintain the superforce decrease. As a result, gravity separates, leaving the electroweak and strong nuclear forces together. At this time, the electromagnetic, weak, and strong forces are identical, matching the conditions requested in the Grand Unification Theory.

The **Inflationary Epoch** $\left(10^{-36} \rightarrow 10^{-32}\ \text{s}\right)$—The separation of the strong nuclear force from the electroweak force during this time is thought to have been responsible for the massive inflation of the universe. Corresponding to the steep diagonal line on the left side of Figure 23.22, the universe may have expanded by a factor of 10^{50} or more in size. In fact, the expansion was so great during this time that it actually occurred faster than the speed of light! Unfortunately, there is little hope that we may be able to test the inflationary scenario directly since it occurs at energies near 10^{14} GeV, vastly greater than the limits of modern accelerators.

The **Electroweak Epoch** $\left(10^{-32} \rightarrow 10^{-11}\ \text{s}\right)$—Now separated from both gravity and the strong nuclear force, the electroweak force exists as a singular force during this time period. As stated earlier, scientists are able to create the energies at this stage in the universe's expansion, needing only 100 GeV, as shown in Figure 23.20. W and Z bosons, as well as the Higgs boson, are released during this time.

The **Quark Era** $\left(10^{-11} \rightarrow 10^{-6}\ \text{s}\right)$—During the Quark Era, the universe has expanded and temperatures have decreased to the point at which all four fundamental forces have separated. Additionally, quarks began to take form as energies decreased.

As the universe expanded, further eras took place, allowing for the existence of hadrons, leptons, and photons, the fundamental particles of the standard model. Eventually, in nucleosynthesis, nuclei would be able to form, and the basic building blocks of atomic matter could take place. Using particle accelerators, we are very much working backwards in an attempt to understand the universe. It is encouraging to see that the macroscopic conditions of the Big Bang align nicely with our submicroscopic particle theory.

Check Your Understanding

19. Is there one grand unified theory or multiple grand unifying theories?
  a. one grand unifying theory
  b. multiple grand unifying theories

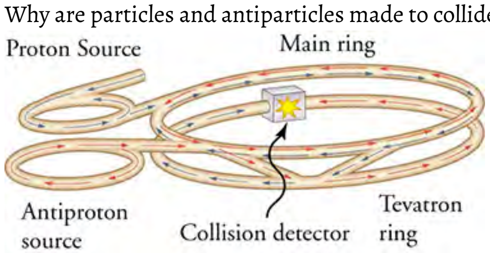
20. In what manner is $E = mc^2$ considered a precursor to the Grand Unified Theory?
  a. The grand unified theory seeks relate the electroweak and strong nuclear forces to one another just as $E = mc^2$ related energy and mass.
  b. The grand unified theory seeks to relate the electroweak force and mass to one another just as $E = mc^2$ related energy and mass.
  c. The grand unified theory seeks to relate the mass and strong nuclear forces to one another just as $E = mc^2$ related energy and mass.
  d. The grand unified theory seeks to relate gravity and strong nuclear force to one another, just as $E = mc^2$ related energy and mass.

21. List the following eras in order of occurrence from the Big Bang: Electroweak Epoch, Grand Unification Epoch, Inflationary Epoch, Planck Epoch, Quark Era.
  a. Quark Era, Grand Unification Epoch, Inflationary Epoch, Electroweak Epoch, Planck Epoch
  b. Planck Epoch, Inflationary Epoch, Grand Unification Epoch, Electroweak Epoch, Quark Era
  c. Planck Epoch, Electroweak Epoch, Grand Unification Epoch, Inflationary Epoch, Quark Era
  d. Planck Epoch, Grand Unification Epoch, Inflationary Epoch, Electroweak Epoch, Quark Era

22. How did the temperature of the universe change as it expanded?
  a. The temperature of the universe increased.
  b. The temperature of the universe decreased.
  c. The temperature of the universe first decreased and then increased.
  d. The temperature of the universe first increased and then decreased.

23. Under current conditions, is it possible for scientists to use particle accelerators to verify the Grand Unified Theory?
  a. No, there is not enough energy.
  b. Yes, there is enough energy.

24. Why are particles and antiparticles made to collide as shown in this image?



  a. Particles and antiparticles have the same mass.
  b. Particles and antiparticles have different mass.
  c. Particles and antiparticles have the same charge.
  d. Particles and antiparticles have opposite charges.

25. The existence of what particles were predicted as a consequence of the electroweak theory?
  a. fermions
  b. Higgs bosons

c. leptons
d. W^+, W^-, and Z° bosons

KEY TERMS

W^+ boson positive carrier particle of the weak nuclear force

W^- boson negative carrier particle of the weak nuclear force

Z^0 boson neutral carrier particle of the weak nuclear force

annihilation the process of destruction that occurs when a particle and antiparticle interact

antimatter matter constructed of antiparticles; antimatter shares most of the same properties of regular matter, with charge being the only difference between many particles and their antiparticle analogues

baryon hadrons that always decay to another baryon

Big Bang a gigantic explosion that threw out matter a few billion years ago

bottom quark a quark flavor

carrier particle a virtual particle exchanged in the transmission of a fundamental force

charmed quark a quark flavor, which is the counterpart of the strange quark

colliding beam head-on collisions between particles moving in opposite directions

color a property of quarks the relates to their interactions through the strong force

cyclotron accelerator that uses fixed-frequency alternating electric fields and fixed magnets to accelerate particles in a circular spiral path

down quark the second lightest of all quarks

Electroweak Epoch the stage before 10^{-11} back to 10^{-34} seconds after the Big Bang

electroweak theory theory showing connections between EM and weak forces

Feynman diagram a graph of time versus position that describes the exchange of virtual particles between subatomic particles

flavor quark type

gluons exchange particles of the nuclear strong force

Grand Unification Epoch the time period from 10^{-43} to 10^{-34} seconds after the Big Bang, when Grand Unification Theory, in which all forces except gravity are identical, governed the universe

Grand Unified Theory theory that shows unification of the strong and electroweak forces

graviton hypothesized particle exchanged between two particles of mass, transmitting the gravitational force between them

hadron particles composed of quarks that feel the strong and weak nuclear force

Higgs boson a massive particle that provides mass to the weak bosons and provides validity to the theory that carrier particles are identical under certain circumstances

Higgs field the field through which all fundamental particles travel that provides them varying mass through the transport of the Higgs boson

Inflationary Epoch the rapid expansion of the universe by an incredible factor of 10^{-50} for the brief time from 10^{-35} to about 10^{-32} seconds

lepton fundamental particles that do not feel the nuclear strong force

meson hadrons that can decay to leptons and leave no hadrons

pair production the creation of a particle and antiparticle, commonly an electron and positron, due to the annihilation of a photon

particle physics the study of and the quest for those truly fundamental particles having no substructure

pion particle exchanged between nucleons, transmitting the strong nuclear force between them

Planck Epoch the earliest era of the universe, before 10^{-43} seconds after the Big Bang

positron a particle of antimatter that has the properties of a positively charged electron

quantum chromodynamics the theory of color interaction between quarks that leads to understanding of the nuclear strong force

quantum electrodynamics the theory of electromagnetism on the particle scale

quark an elementary particle and fundamental constituent of matter that is a substructure of hadrons

Quark Era the time period from 10^{-11} to 10^{-6} seconds at which all four fundamental forces are separated and quarks begin to exit

Standard Model an organization of fundamental particles and forces that is a result of quantum chromodynamics and electroweak theory

strange quark the third lightest of all quarks

superforce the unification of all four fundamental forces into one force

synchrotron a version of a cyclotron in which the frequency of the alternating voltage and the magnetic field strength are increased as the beam particles are accelerated

Theory of Everything the theory that shows unification of all four fundamental forces

top quark a quark flavor

up quark the lightest of all quarks

weak nuclear force fundamental force responsible for particle decay

SECTION SUMMARY

23.1 The Four Fundamental Forces

- The four fundamental forces are gravity, the electromagnetic force, the weak nuclear force, and the strong nuclear force.
- A variety of particle accelerators have been used to explore the nature of subatomic particles and to test predictions of particle theories.

23.2 Quarks

- There are three types of fundamental particles—leptons, quarks, and carrier particles.
- Quarks come in six flavors and three colors and occur only in combinations that produce white.
- Hadrons are thought to be composed of quarks, with baryons having three quarks and mesons having a quark and an antiquark.
- Known particles can be divided into three major groups—leptons, hadrons, and carrier particles (gauge bosons).
- All particles of matter have an antimatter counterpart that has the opposite charge and certain other quantum numbers. These matter–antimatter pairs are otherwise very similar but will annihilate when brought together.
- The strong force is carried by eight proposed particles called gluons, which are intimately connected to a quantum number called color—their governing theory is thus called quantum chromodynamics (QCD). Taken together, QCD and the electroweak theory are widely accepted as the Standard Model of particle physics.

23.3 The Unification of Forces

- Attempts to show unification of the four forces are called Grand Unified Theories (GUTs) and have been partially successful, with connections proven between EM and weak forces in electroweak theory.
- Unification of the strong force is expected at such high energies that it cannot be directly tested, but it may have observable consequences in the as-yet-unobserved decay of the proton. Although unification of forces is generally anticipated, much remains to be done to prove its validity.

CHAPTER REVIEW

Concept Items

23.1 The Four Fundamental Forces

1. What forces does the inverse square law describe?
   a. the electromagnetic and weak nuclear force
   b. the electromagnetic force and strong nuclear force
   c. the electromagnetic force and gravity
   d. the strong nuclear force and gravity

2. Do the carrier particles explain the loss of mass in nuclear decay?
   a. no
   b. yes

3. What happens to the rate of voltage oscillation within a synchrotron each time the particle completes a loop?
   a. The rate of voltage oscillation increases as the particle travels faster and faster on each loop.
   b. The rate of voltage oscillation decreases as the particle travels faster and faster on each loop.
   c. The rate of voltage oscillation remains the same each time the particle completes a loop.
   d. The rate of voltage oscillation first increases and then remains constant each time the particle completes a loop.

4. Which of the four forces is responsible for ionic bonding?
   a. electromagnetic force
   b. gravity
   c. strong force
   d. weak nuclear force

5. What type of particle accelerator uses oscillating electric fields to accelerate particles around a fixed radius track?
   a. LINAC
   b. synchrotron
   c. SLAC
   d. Van de Graaff accelerator

23.2 Quarks

6. How does the charge of an individual quark determine hadron structure?
   a. Since the hadron must have an integral value, the individual quarks must be combined such that the average of their charges results in the value of a quark.
   b. Since the hadron must have an integral value, the individual atoms must be combined such that the sum of their charges is less than zero.
   c. The individual quarks must be combined such that the product of their charges is equal to the total charge of the hadron structure.
   d. Since the hadron must have an integral value of charge, the individual quarks must be combined such that the sum of their charges results in an

integral value.

7. Why do leptons not feel the strong nuclear force?
   a. Gluons are the carriers of the strong nuclear force that interacts between quarks through color interactions, but leptons are constructed of quarks that do not have gluons.
   b. Gluons are the carriers of the strong nuclear force that interacts between quarks through mass interactions, but leptons are not constructed of quarks and are not massive.
   c. Gluons are the carriers of the strong nuclear force that interacts between quarks through mass interactions, but leptons are constructed of the quarks that are not massive.
   d. Gluons are the carriers of the strong nuclear force that interacts between quarks through color interactions, but leptons are not constructed of quarks, nor do they have color constituents.

8. What property commonly distinguishes antimatter from its matter analogue?
   a. mass
   b. charge
   c. energy
   d. speed

9. Can the Standard Model change as new information is gathered?
   a. yes
   b. no

10. What is the relationship between the Higgs field and the Higgs boson?
   a. The Higgs boson is the carrier that transfers force for the Higgs field.
   b. The Higgs field is the time duration over which the Higgs particles transfer force to the other particles.
   c. The Higgs field is the magnitude of momentum transferred by the Higgs particles to the other particles.
   d. The Higgs field is the magnitude of torque transfers by the Higgs particles on the other particles.

11. What were the original three flavors of quarks discovered?
   a. up, down, and charm
   b. up, down, and bottom
   c. up, down, and strange
   d. up, down, and top

12. Protons are more massive than electrons. The three quarks in the proton account for only a small amount of this mass difference. What accounts for the remaining excess mass in protons compared to electrons?
   a. The highly energetic gluons connecting the quarks account for the remaining excess mass in protons compared to electrons.
   b. The highly energetic photons connecting the quarks account for the remaining excess mass in protons compared to electrons.
   c. The antiparallel orientation of the quarks present in a proton accounts for the remaining excess mass in protons compared to electrons.
   d. The parallel orientation of the quarks present in a proton accounts for the remaining excess mass in protons compared to electrons.

23.3 The Unification of Forces

13. Why is the unification of fundamental forces important?
   a. The unification of forces will help us understand fundamental structures of the universe.
   b. The unification of forces will help in the proof of the graviton.
   c. The unification of forces will help in achieving a speed greater than the speed of light.
   d. The unification of forces will help in studying antimatter particles.

14. Why are scientists unable to model the conditions of the universe at time periods shortly after the Big Bang?
   a. The amount of energy necessary to replicate the Planck Epoch is too high.
   b. The amount of energy necessary to replicate the Planck Epoch is too low.
   c. The volume of setup necessary to replicate the Planck Epoch is too high.
   d. The volume of setup necessary to replicate the Planck Epoch is too low.

15. What role does proton decay have in the search for GUTs?
   a. Proton decay is a premise of a number of GUTs.
   b. Proton decay negates the validity of a number of GUTs.

16. What is the name for the theory of unification of all four fundamental forces?
   a. the theory of everything
   b. the theory of energy-to-mass conversion
   c. the theory of relativity
   d. the theory of the Big Bang

17. Is it easier for scientists to find evidence for the Grand Unified Theory or the Theory of Everything? Explain.
   a. Theory of Everything, because it requires 10^{19} GeV of energy
   b. Theory of Everything, because it requires 10^{14} GeV of energy
   c. Grand Unified Theory, because it requires

10^{19} GeV of energy

d. Grand Unified Theory, because it requires 10^{14} GeV of energy

Critical Thinking Items

23.1 The Four Fundamental Forces

18. The gravitational force is considered a very weak force. Yet, it is strong enough to hold Earth in orbit around the Sun. Explain this apparent disparity.

a. At the level of the Earth-to-Sun distance, gravity is the strongest acting force because neither the strong nor the weak nuclear force exists at this distance.
b. At the level of the Earth-to-Sun distance, gravity is the strongest acting force because both the strong and the weak nuclear force is minimal at this distance.

19. True or False—Given that their carrier particles are massless, some may argue that the electromagnetic and gravitational forces should maintain the same value at all distances from their source. However, both forces decrease with distance at a rate of $\frac{1}{r}$

a. false
b. true

20. Why is a stationary target considered inefficient in a particle accelerator?

a. The stationary target recoils upon particle strike, thereby transferring much of the particle's energy into its motion. As a result, a greater amount of energy goes into breaking the particle into its constituent components.
b. The stationary target contains zero kinetic energy, so it requires more energy to break the particle into its constituent components.
c. The stationary target contains zero potential energy, so it requires more energy to break the particle into its constituent components.
d. The stationary target recoils upon particle strike, transferring much of the particle's energy into its motion. As a result, a lesser amount of energy goes into breaking the particle into its constituent components.

21. Compare the total strong nuclear force in a lithium atom to the total strong nuclear force in a lithium ion (Li^{+1}).

a. The total strong nuclear force in a lithium atom is thrice the total strong nuclear force in a lithium ion.
b. The total strong nuclear force in a lithium atom is twice the total strong nuclear force in a lithium ion.
c. The total strong nuclear force in a lithium atom is the same as the total strong nuclear force in a lithium ion.
d. The total strong nuclear force in a lithium atom is half the total strong nuclear force in a lithium ion.

23.2 Quarks

22. Explain why it is not possible to find a particle composed of just two quarks.

a. A particle composed of two quarks will have an integral charge and a white color. Hence, it cannot exist.
b. A particle composed of two quarks will have an integral charge and a color that is not white. Hence, it cannot exist.
c. A particle composed of two quarks will have a fractional charge and a white color. Hence, it cannot exist.
d. A particle composed of two quarks will have a fractional charge and a color that is not white. Hence, it cannot exist.

23. Why are mesons considered unstable?

a. Mesons are composites of two antiparticles that quickly annihilate each other.
b. Mesons are composites of two particles that quickly annihilate each other.
c. Mesons are composites of a particle and antiparticle that quickly annihilate each other.
d. Mesons are composites of two particles and one antiparticle that quickly annihilate each other.

24. Does antimatter have a negative mass?

a. No, antimatter does not have a negative mass.
b. Yes, antimatter does have a negative mass.

25. What similarities exist between the Standard Model and the periodic table of elements?

a. During their invention, both the Standard Model and the periodic table organized material by mass.
b. At the times of their invention, both the Standard Model and the periodic table organized material by charge.
c. At the times of their invention, both the Standard Model and the periodic table organized material by interaction with other available particles.
d. At the times of their invention, both the Standard Model and the periodic table organized material by size.

26. How were particle collisions used to provide evidence of the Higgs boson?

a. Because some particles do not contain the Higgs boson, the collisions of such particles will cause their destruction.
b. Because only the charged particles contain the Higgs boson, the collisions of such particles will cause their destruction and will expel the Higgs boson.
c. Because all particles with mass contain the Higgs boson, the collisions of such particles will cause their destruction and will absorb the Higgs boson.
d. Because all particles with mass contain the Higgs boson, the collisions of such particles will cause their destruction and will expel the Higgs boson.

27. Explain how the combination of a quark and antiquark can result in the creation of a hadron.
a. The combination of a quark and antiquark can result in a particle with an integer charge and color of white, therefore satisfying the properties for a hadron.
b. The combination of a quark and antiquark must result in a particle with a negative charge and color of white, therefore satisfying the properties for a hadron.
c. The combination of a quark and antiquark can result in a particle with an integer charge and color that is not white, therefore satisfying the properties for a hadron.
d. The combination of a quark and antiquark can result in particle with a fractional charge and color that is not white, therefore satisfying the properties for a hadron.

23.3 The Unification of Forces

28. Why does the strength of the strong force diminish under high-energy conditions?
a. Under high-energy conditions, particles interacting under the strong force will be compressed closer together. As a result, the force between them will decrease.
b. Under high-energy conditions, particles interacting under the strong force will start oscillating. As a result, the force between them will increase.
c. Under high-energy conditions, particles interacting under the strong force will have high velocity. As a result, the force between them will decrease.
d. Under high-energy conditions, particles interacting under the strong force will start moving randomly. As a result, the force between them will decrease.

29. If some unknown cause of the red shift, such as light becoming *tired* from traveling long distances through empty space, is discovered, what effect would there be on cosmology?
a. The effect would be substantial, as the Big Bang is based on the idea that the red shift is evidence that galaxies are moving toward one another.
b. The effect would be substantial, as the Big Bang is based on the idea that the red shift is evidence that the galaxies are moving away from one another.
c. The effect would be substantial, as the Big Bang is based on the idea that the red shift is evidence that galaxies are neither moving away from nor moving toward one another.
d. The effect would be substantial, as the Big Bang is based on the idea that the red shift is evidence that galaxies are sometimes moving away from and sometimes moving toward one another.

30. How many molecules of water are necessary if scientists wanted to check the 10^{31} -yr estimate of proton decay within the course of one calendar year?
a. 10^{29} molecules
b. 10^{30} molecules
c. 10^{31} molecules
d. 10^{32} molecules

31. As energy of interacting particles increases toward the theory of everything, the gravitational force between them increases. Why does this occur?
a. As energy increases, the masses of the interacting particles will increase.
b. As energy increases, the masses of the interacting particles will decrease.
c. As energy increases, the masses of the interacting particles will remain constant.
d. As energy increases, the masses of the interacting particles starts changing (increasing or decreasing). As a result, the gravitational force between the particles will increase.

Performance Task

23.3 The Unification of Forces

32. Communication is an often overlooked and useful skill for a scientist, especially in a competitive field where financial resources are limited. Scientists are often required to explain their findings or the relevance of their work to agencies within the government in order to maintain funding to continue their research. Let's say you are an ambitious young particle physicist, heading an expensive project, and you need to justify its existence to the appropriate funding agency. Write a brief paper (about one page) explaining why molecular-level structure is important in the functioning of designed materials in a specific industry.
    - First, think of an industry where molecular-level structure is important.
    - Research what materials are used in that industry as well as what are the desired properties of the materials.
    - What molecular-level characteristics lead to what properties?

    One example would be explaining how flexible but durable materials are made up of long-chained molecules and how this is useful for finding more environmentally friendly alternatives to plastics. Another example is explaining why electrically conductive materials are often made of metal and how this is useful for developing better batteries.

TEST PREP

Multiple Choice

23.1 The Four Fundamental Forces

33. Which of the following is not one of the four fundamental forces?
    a. gravity
    b. friction
    c. strong nuclear
    d. electromagnetic

34. What type of carrier particle has not yet been found?
    a. gravitons
    b. W bosons
    c. Z bosons
    d. pions

35. What effect does an increase in electric potential have on the accelerating capacity of a Van de Graaff generator?
    a. It increases accelerating capacity.
    b. It decreases accelerating capacity.
    c. The accelerating capacity of a Van de Graaff generator is constant regardless of electric potential.
    d. Van de Graaff generators do not have the capacity to accelerate particles.

36. What force or forces exist between a proton and a second proton?
    a. The weak electrostatic force and strong magnetic force
    b. The weak electrostatic and strong gravitational force
    c. The weak frictional force and strong gravitational force
    d. The weak nuclear force, the strong nuclear force, and the electromagnetic force

23.2 Quarks

37. To what color must quarks combine for a particle to be constructed?
    a. black
    b. green
    c. red
    d. white

38. What type of hadron is always constructed partially of an antiquark?
    a. baryon
    b. lepton
    c. meson
    d. photno

39. What particle is typically released when two particles annihilate?
    a. graviton
    b. antimatter
    c. pion
    d. photno

40. Which of the following categories is not one of the three main categories of the Standard Model?
    a. gauge bosons
    b. hadrons
    c. leptons
    d. quarks

41. Analysis of what particles began the search for the Higgs boson?
    a. W and Z bosons
    b. up and down quarks
    c. mesons and baryons

d. neutrinos and photons

42. What similarities exist between the discovery of the quark and the discovery of the neutron?
a. Both the quark and the neutron were discovered by launching charged particles through an unknown structure and observing the particle recoil.
b. Both the quark and the neutron were discovered by launching electrically neutral particles through an unknown structure and observing the particle recoil.
c. Both quarks and neutrons were discovered by studying their deflection under an electric field.

23.3 The Unification of Forces

43. Which two forces were first combined, signifying the eventual desire for a Grand Unified Theory?
a. electric force and magnetic forces
b. electric force and weak nuclear force
c. gravitational force and the weak nuclear force
d. electroweak force and strong nuclear force

44. After the Big Bang, what was the first force to separate from the others?
a. electromagnetic force
b. gravity
c. strong nuclear force
d. weak nuclear force

45. What is the name of the device used by scientists to check for proton decay?
a. the cyclotron
b. the Large Hadron Collider
c. the Super-Kamiokande
d. the synchrotron

46. How do Feynman diagrams suggest the Grand Unified Theory?
a. The electromagnetic, weak, and strong nuclear forces all have similar Feynman diagrams.
b. The electromagnetic, weak, and gravitational forces all have similar Feynman diagrams.
c. The electromagnetic, weak, and strong forces all have different Feynman diagrams.

Short Answer

23.1 The Four Fundamental Forces

47. Why do people tend to be more aware of the gravitational and electromagnetic forces than the strong and weak nuclear forces?
a. The gravitational and electromagnetic forces act at short ranges, while strong and weak nuclear forces act at comparatively long range.
b. The strong and weak nuclear forces act at short ranges, while gravitational and electromagnetic forces act at comparatively long range.
c. The strong and weak nuclear forces act between all objects, while gravitational and electromagnetic forces act between smaller objects.
d. The strong and weak nuclear forces exist in outer space, while gravitational and electromagnetic forces exist everywhere.

48. What fundamental force is responsible for the force of friction?
a. the electromagnetic force
b. the strong nuclear force
c. the weak nuclear force

49. How do carrier particles relate to the concept of a force field?
a. Carrier particles carry mass from one location to another within a force field.
b. Carrier particles carry force from one location to another within a force field.
c. Carrier particles carry charge from one location to another within a force field.
d. Carrier particles carry volume from one location to another within a force field.

50. Which carrier particle is transmitted solely between nucleons?
a. graviton
b. photon
c. pion
d. W and Z bosons

51. Two particles of the same mass are traveling at the same speed but in opposite directions when they collide head-on.
What is the final kinetic energy of this two-particle system?
a. infinite
b. the sum of the kinetic energies of the two particles
c. zero
d. the product of the kinetic energies of the two particles

52. Why do colliding beams result in the location of smaller particles?
a. Colliding beams create energy, allowing more energy to be used to separate the colliding particles.
b. Colliding beams lower the energy of the system, so it requires less energy to separate the colliding particles.
c. Colliding beams reduce energy loss, so less energy

is required to separate colliding particles.
d. Colliding beams reduce energy loss, allowing more energy to be used to separate the colliding particles.

23.2 Quarks

53. What two features of quarks determine the structure of a particle?
a. the color and charge of individual quarks
b. the color and size of individual quarks
c. the charge and size of individual quarks
d. the charge and mass of individual quarks

54. What fundamental force does quantum chromodynamics describe?
a. the weak nuclear force
b. the strong nuclear force
c. the electromagnetic force
d. the gravitational force

55. Is it possible for a baryon to be constructed of two quarks and an antiquark?
a. Yes, the color of the three particles would be able to sum to white.
b. No, the color of the three particles would not be able to sum to white.

56. Can baryons be more massive than mesons?
a. no
b. yes

57. If antimatter exists, why is it so difficult to find?
a. There is a smaller amount of antimatter than matter in the universe; antimatter is quickly annihilated by its matter analogue.
b. There is a smaller amount of matter than antimatter in the universe; matter is annihilated by its antimatter analogue.
c. There is a smaller amount of antimatter than matter in universe; antimatter and its matter analogue coexist.
d. There is a smaller amount of matter than antimatter in the universe; matter and its antimatter analogue coexist.

58. Does a neutron have an antimatter counterpart?
a. No, the antineutron does not exist.
b. Yes, the antineutron does exist.

59. How are the four fundamental forces incorporated into the Standard Model of the atom?
a. The four fundamental forces are represented by their carrier particles, the electrons.
b. The four fundamental forces are represented by their carrier particles, the gauge bosons.
c. The four fundamental forces are represented by their carrier particles, the leptons.
d. The four fundamental forces are represented by their carrier particles, the quarks.

60. Which particles in the Standard Model account for the majority of matter with which we are familiar?
a. particles in fourth column of the Standard Model
b. particles in third column of the Standard Model
c. particles in the second column of the Standard Model
d. particles in the first column of the Standard Model

61. How can a particle gain mass by traveling through the Higgs field?
a. The Higgs field slows down passing particles; the decrease in kinetic energy is transferred to the particle's mass.
b. The Higgs field accelerates passing particles; the decrease in kinetic energy is transferred to the particle's mass.
c. The Higgs field slows down passing particles; the increase in kinetic energy is transferred to the particle's mass.
d. The Higgs field accelerates passing particles; the increase in kinetic energy is transferred to the particle's mass.

62. How does mass-energy conservation relate to the Higgs field?
a. The increase in a particle's energy when traveling through the Higgs field is countered by its increase in mass.
b. The decrease in a particle's kinetic energy when traveling through the Higgs field is countered by its increase in mass.
c. The decrease in a particle's energy when traveling through the Higgs field is countered by its decrease in mass.
d. The increase in a particle's energy when traveling through the Higgs field is countered by its decrease in mass.

23.3 The Unification of Forces

63. Why do scientists believe that the strong nuclear force and the electroweak force will combine under high energies?
a. The electroweak force will have greater strength.
b. The strong nuclear force and electroweak force will achieve the same strength.
c. The strong nuclear force will have greater strength.

64. At what energy will the strong nuclear force theoretically unite with the electroweak force?

a. 10^{12} eV
b. 10^{13} eV
c. 10^{14} eV
d. 10^{15} eV

65. While we can demonstrate the unification of certain forces within the laboratory, for how long were the four forces naturally unified within the universe?
a. 10^{-43} seconds
b. 10^{-41} seconds
c. 10^{-39} seconds
d. 10^{-38} seconds

66. How does the search for the Grand Unified Theory help test the standard cosmological model?
a. Scientists are increasing energy in the lab that models the energy in earlier, denser stages of the universe.
b. Scientists are increasing energy in the lab that models the energy in earlier, less dense stages of the universe.
c. Scientists are decreasing energy in the lab that models the energy in earlier, denser stages of the universe.
d. Scientists are decreasing energy in the lab that models the energy in earlier, less dense stages of the universe.

67. Why does finding proof that protons do not decay not disprove all GUTs?
a. Proton decay is not a premise of all GUTs, and current GUTs can be amended in response to new findings.
b. Proton decay is a premise of all GUTs, but current GUTs can be amended in response to new findings.

68. When accelerating elementary particles in a particle accelerator, they quickly achieve a speed approaching the speed of light. However, as time continues, the particles maintain this speed yet continue to increase their kinetic energy. How is this possible?
a. The speed remains the same, but the masses of the particles increase.
b. The speed remains the same, but the masses of the particles decrease.
c. The speed remains the same, and the masses of the particles remain the same.
d. The speed and masses will remain the same, but temperature will increase.

Extended Response

23.1 The Four Fundamental Forces

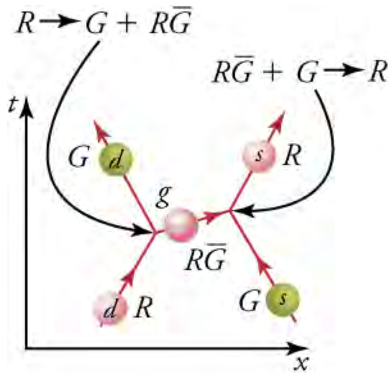
69. If the strong attractive force is the greatest of the four fundamental forces, are all masses fated to combine together at some point in the future? Explain.
a. No, the strong attractive force acts only at incredibly small distances. As a result, only masses close enough to be within its range will combine.
b. No, the strong attractive force acts only at large distances. As a result, only masses far enough apart will combine.
c. Yes, the strong attractive force acts at any distance. As a result, all masses are fated to combine together at some point in the future.
d. Yes, the strong attractive force acts at large distances. As a result, all masses are fated tocombine together at some point in the future.

70. How does the discussion of carrier particles relate to the concept of relativity?
a. Calculations of mass and energy during their transfer are relativistic, because carrier particles travel more slowly than the speed of sound.
b. Calculations of mass and energy during their transfer are relativistic, because carrier particles travel at or near the speed of light.
c. Calculations of mass and energy during their transfer are relativistic, because carrier particles travel at or near the speed of sound.
d. Calculations of mass and energy during their transfer are relativistic, because carrier particles travel faster than the speed of light.

71. Why are synchrotrons constructed to be very large?
a. By using a large radius, high particle velocities can be achieved using a large centripetal force created by large electromagnets.
b. By using a large radius, high particle velocities can be achieved without a large centripetal force created by large electromagnets.
c. By using a large radius, the velocities of particles can be reduced without a large centripetal force created by large electromagnets.
d. By using a large radius, the acceleration of particles can be decreased without a large centripetal force created by large electromagnets.

23.2 Quarks

72. In this image, how does the emission of the gluon cause the down quark to change from a red color to a green color?



a. The emitted red gluon is made up of a green and a red color. As a result, the down quark changes from a red color to a green color.
b. The emitted red gluon is made up of an anti-green and an anti-red color. As a result, the down quark changes from a red color to a green color.
c. The emitted red gluon is made up of a green and an anti-red color. As a result, the down quark changes from a red color to a green color.
d. The emitted red gluon is made up of an anti-green and a red color. As a result, the down quark changes from a red color to a green color.

73. Neutrinos are much more difficult for scientists to find when compared to other hadrons and leptons. Why is this?
a. Neutrinos are hadrons, and they lack charge.
b. Neutrinos are not hadrons, and they lack charge.
c. Neutrinos are hadrons, and they have positive charge.
d. Neutrinos are not hadrons, and they have a positive charge.

74. What happens to the masses of a particle and its antiparticle when the two annihilate at low energies?
a. The masses of the particle and antiparticle are transformed into energy in the form of photons.
b. The masses of the particle and antiparticle are converted into kinetic energy of the particle and antiparticle respectively.
c. The mass of the antiparticle is converted into kinetic energy of the particle.
d. The mass of the particle is converted into radiation energy of the antiparticle.

75. When a star erupts in a supernova explosion, huge numbers of electron neutrinos are formed in nuclear reactions. Such neutrinos from the 1987A supernova in the relatively nearby Magellanic Cloud were observed within hours of the initial brightening, indicating that they traveled to earth at approximately the speed of light. Explain how this data can be used to set an upper limit on the mass of the neutrino.
a. If the velocity of the neutrino is known, then the upper limit on mass of the neutrino can be set.
b. If only the kinetic energy of the neutrino is known, then the upper limit on mass of the neutrino can be set.
c. If either the velocity or the kinetic energy is known, then the upper limit on the mass of the neutrino can be set.
d. If both the kinetic energy and the velocity of the neutrino are known, then the upper limit on the mass of the neutrino can be set.

76. The term *force carrier particle* is shorthand for the scientific term *vector gauge boson*. From that perspective, can the Higgs boson truly be considered a *force carrier particle*?
a. No, the mass quality provided by the Higgs boson is a scalar quantity.
b. Yes, the mass quality provided by the Higgs boson results in a change of particle's direction.

23.3 The Unification of Forces

77. If a Grand Unified Theory is proven and the four forces are unified, it will still be correct to say that the orbit of the Moon is determined by the gravitational force. Explain why.
a. Gravity will not be a property of the unified force.
b. Gravity will be one property of the unified force.
c. Apart from gravity, no other force depends on the mass of the object.
d. Apart from gravity, no other force can make an object move in a fixed orbit.

78. As the universe expanded and temperatures dropped, the strong nuclear force separated from the electroweak force. Is it likely that under cooler conditions, the force of electricity will separate from the force of magnetism?
a. No, the electric force relies on the magnetic force and vice versa.
b. Yes, the electric and magnetic forces can be separated from each other.

79. Two pool balls collide head-on and stop. Their original kinetic energy is converted to heat and sound. Given that this is not possible for particles, what happens to their converted energy?
a. The kinetic energy is converted into relativistic potential energy, governed by the equation $E = \lambda mch$.
b. The kinetic energy is converted into relativistic mass, governed by the equation $E = \lambda m^2 c$.
c. The kinetic energy is converted into relativistic potential energy, governed by the equation $E = \lambda mgh$.

d. Their kinetic energy is converted into relativistic mass, governed by the equation $E = \lambda mc^2$.

APPENDIX A

Reference Tables

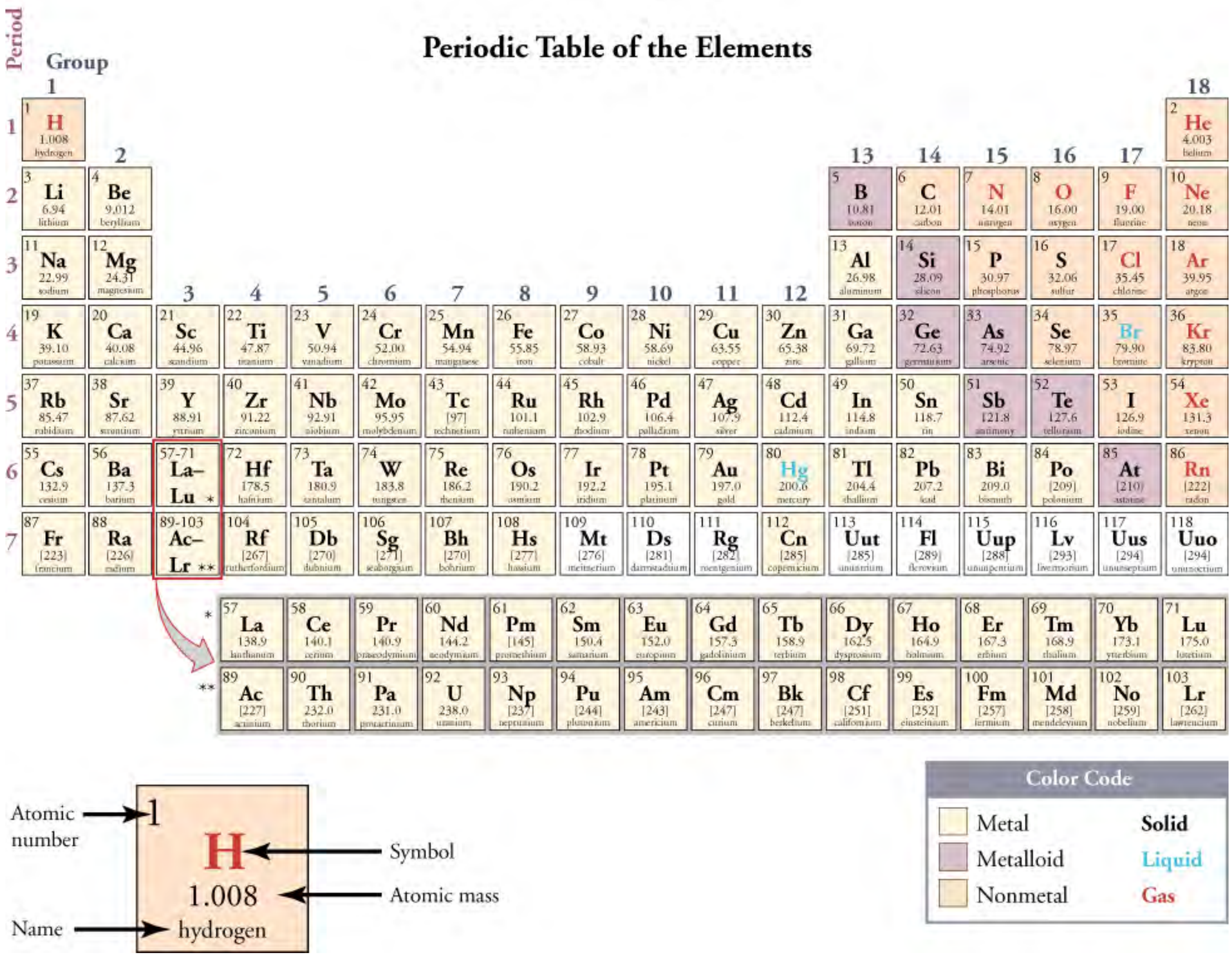


Figure A1 Periodic Table of Elements

Prefix	Symbol	Value	Prefix	Symbol	Value
tera	T	10^{12}	deci	d	10^{-1}
giga	G	10^{9}	centi	c	10^{-2}
mega	M	10^{6}	milli	m	10^{-3}
kilo	k	10^{3}	micro	µ	10^{-6}
hecto	h	10^{2}	nano	n	10^{-9}
deka	da	10^{1}	pico	p	10^{-12}

Table A1 Metric Prefixes for Powers of Ten and Their Symbols

Prefix	Symbol	Value	Prefix	Symbol	Value
___		10^0	femto	f	10^{-15}

Table A1 Metric Prefixes for Powers of Ten and Their Symbols

	Entity	Abbreviation	Name
Fundamental units	Length	m	meter
	Mass	kg	kilogram
	Time	s	second
	Current	A	ampere
Supplementary unit	Angle	rad	radian
Derived units	Force	$N = kg \cdot \frac{m}{s^2}$	newton
	Energy	$J = kg \cdot m^2$	joule
	Power	$W = \frac{J}{s}$	watt
	Pressure	$Pa = \frac{N}{m^2}$	pascal
	Frequency	$Hz = \frac{1}{s}$	hertz
	Electronic potential	$V = \frac{J}{C}$	volt
	Capacitance	$F = \frac{C}{V}$	farad
	Charge	$C = s \cdot A$	coulomb
	Resistance	$\Omega = \frac{V}{A}$	ohm
	Magnetic field	$T = \frac{N}{A \cdot m}$	tesla
	Nuclear decay rate	$Bq = \frac{1}{s}$	becquerel

Table A2 SI Units

Length	1 inch (in.) = 2.54 cm (exactly)
	1 foot (ft) = 0.3048 m
	1 mile (mi) = 1.609 km

Table A3 Selected British Units

Force	1 pound (lb) = 4.448 N
Energy	1 British thermal unit (Btu) = 1.055×10^3 J
Power	1 horsepower (hp) = 746 W
Pressure	1 lb/in^2 = 6.895×10^3 Pa

Table A3 Selected British Units

Length	1 light year (ly) = 9.46×10^{15} m
	1 astronomical unit (au) = 1.50×10^{11} m
	1 nautical mile = 1.852 km
	1 angstrom(Å) = 10^{-10} m
Area	1 acre (ac) = 4.05×10^3 m2
	1 square foot (ft^2) 9.29×10^{-2} m^3
	1 barn (*b*) = 10^{-28} m^2
Volume	1 liter (*L*) = 10^{-3} m^3
	1 U.S. gallon (gal) = 3.785×10^{-3} m^3
Mass	1 solar mass = 1.99×10^{30} kg
	1 metric ton = 10^3 kg
	1 atomic mass unit (*u*) = 1.6605×10^{-27} kg
Time	1 year (*y*) = 3.16×10^7 s
	1 day (*d*) = 86,400 s
Speed	1 mile per hour (mph) = 1.609 km / h
	1 nautical mile per hour (naut) = 1.852 km / h
Angle	1 degree (°) = 1.745x10^{-2} rad
	1 minute of arc (') = 1 / 60 degree
	1 second of arc ('') = 1 / 60 minute of arc
	1 grad = 1.571×10^{-2} rad

Table A4 Other Units

Energy	1 kiloton TNT (kT) = 4.2×10^{12} J
	1 kilowatt hour (kW · *h*) = 3.60 × 106 J
	1 food calorie (kcal) = 4186 J
	1 calorie (cal) = 4.186 J
	1 electron volt (cV) = 1.60×10^{-19} J
Pressure	1 atmosphere (atm) = 1.013×10^{5} Pa
	1 millimeter of mercury (mm Hg) = 133.3 Pa
	1 torricelli (torr) = 1 mm Hg = 133.3 Pa
Nuclear decay rate	1 curie (Ci) = 3.70×10^{10} Bq

Table A4 Other Units

Circumference of a circle with radius *r* or diameter *d*	$C = 2\pi = \pi d$
Area of a circle with radius *r* or diameter *d*	$A = \pi r^2 = \pi d^2/4$
Area of a sphere with radius *r*	$A = 4\pi r^2$
Volume of a sphere with radius *r*	$V = (4/3)\,(\pi r^3)$

Table A5 Useful formulae

Symbol	Meaning	Best Value	Approximate Value
c	Speed of light in vacuum	$2.99792458 \times 10^{8}\,\text{m/s}$	$3.00 \times 10^{8}\,\text{m/s}$
G	Gravitational constant	$6.67384\,(80) \times 10^{-11}\,\text{N} \cdot \text{m}^2/\text{kg}^2$	$6.67 \times 10^{-11}\,\text{N} \cdot \text{m}^2/\text{kg}^2$
^{N}A	Avogadro's number	$6.02214129\,(27) \times 10^{23}\,\text{J/K}$	6.02×10^{23}
k	Boltzmann's constant	$1.3806488\,(13) \times 10^{-23}\,\text{J/K}$	$1.38 \times 10^{-23}\,\text{J/K}$
R	Gas constant	$8.3144621\,(75)\ \text{J/mol} \cdot \text{K}$	$8.31\ \text{J/mol} \cdot \text{K} = 1.99\ \text{cal/mol} \cdot \text{K}$ $= 0.0821\ \text{atm} \cdot \text{L/mol} \cdot \text{K}$
σ	Stefan-Boltzmann Constant	$5.670373\,(21) \times 10^{-8}\,\text{W/m}^2 \cdot \text{K}$	$5.67 \times 10^{-8}\,\text{W/m}^2 \cdot \text{K}$
k	Coulomb force constant	$8.987551788... \times 10^{9}\,\text{N} \cdot \text{m}^2/\text{C}^2$	$8.99 \times 10^{9}\,\text{N} \cdot \text{m}^2/\text{C}^2$

Table A6 Important Constants

Symbol	Meaning	Best Value	Approximate Value
q_e	Charge on electron	$-1.602176565\,(35) \times 10^{-19}\,\text{C}$	$-1.60 \times 10^{-19}\,\text{C}$
ε_0	Permittivity of free space	$8.854187817... \times 10^{-12}\,\text{C}^2/\text{N}\cdot\text{m}^2$	$8.85 \times 10^{-12}\,\text{C}^2/\text{N}\cdot\text{m}^2$
μ_0	Permeability of free space	$4\pi \times 10^{-7}\,\text{T}\cdot\text{m/A}$	$1.26 \times 10^{-6}\,\text{T}\cdot\text{m/A}$
h	Planck's constant	$6.62606957\,(29) \times 10^{-34}\,\text{J}\cdot\text{s}$	$6.63 \times 10^{-34}\,\text{J}\cdot\text{s}$

Table A6 Important Constants

Alpha	Α	α
Beta	Β	β
Gamma	Γ	γ
Delta	Δ	δ
Epsilon	Ε	ε
Zeta	Ζ	ζ
Eta	Η	η
Theta	Θ	θ
Iota	Ι	ι
Kappa	Κ	κ
Lambda	Λ	λ
Mu	Μ	μ
Nu	Ν	ν
Xi	Ξ	ξ
Omicron	Ο	ο
Pi	Π	π
Rho	Ρ	ρ
Sigma	Σ	σ
Tau	Τ	τ

Table A7 The Greek Alphabet

Upsilon	Υ	υ
Phi	Φ	ϕ
Chi	Χ	χ
Psi	Ψ	ψ
Omega	Ω	ω

Table A7 The Greek Alphabet

Sun	mass	1.99×10^{30} kg
	average radius	6.96×10^{8} m
	Earth-sun distance (average)	1.496×10^{11} m
Earth	mass	5.9736×10^{24} kg
	average radius	6.376×10^{6} m
	orbital period	3.16×10^{7} s
Moon	mass	7.35×10^{22} kg
	average radius	1.74×10^{6} s
	orbital period (average)	2.36×10^{6} s
	Earth-moon distance (average)	3.84×10^{8} m

Table A8 Solar System Data

Atomic number, Z	Name	Atomic Mass Number, A	Symbol	Atomic Mass (u)	Percent Abundance or Decay Mode	Half-life, $t_{1/2}$
0	neutron	1	*n*	1.008 665	β^-	10.37 min
1	Hydrogen	1	^1H	1.007 825	99.985%	
	Deuterium	2	^2H or D	2.014 102	0.015%	
	Tritium	3	^3H or T	3.016 050	β^-	12.33 y
2	Helium	3	^3He	3.016 030	1.38×10^{-4} %	

Table A9 Atomic Masses and Decay

Atomic number, Z	Name	Atomic Mass Number, A	Symbol	Atomic Mass (u)	Percent Abundance or Decay Mode	Half-life, ^{t}1/2
		4	^{4}He	4.002 603	≈100%	
3	Lithium	6	^{6}Li	6.015 121	7.5%	
		7	^{7}Li	7.016 003	92.5%	
4	Beryllium	7	^{7}Be	7.016 928	EC	53.29 d
		9	^{9}Be	9.012 182	100%	
5	Boron	10	^{10}B	10.012 937	19.9%	
		11	^{11}B	11.009 305	80.1%	
6	Carbon	11	^{11}C	11.011 432	EC, β^{+}	
		12	^{12}C	12.000 000	98.90%	
		13	^{13}C	13.003 355	1.10%	
		14	^{14}C	14.003 241	β^{-}	5730 y
7	Nitrogen	13	^{12}N	13.005 738	β^{+}	9.96 min
		14	^{13}N	14.003 074	99.63%	
		15	^{14}N	15.000 108	0.37%	
8	Oxygen	15	^{15}O	15.003 065	EC, β^{+}	122 s
		16	^{16}O	15.994 915	99.76%	
		18	^{18}O	17.999 160	0.200%	
9	Fluorine	18	^{18}F	18.000 937	EC, β^{+}	1.83 h
		19	^{19}F	18.998 403	100%	
10	Neon	20	^{20}Ne	19.992 435	90.51%	
		22	^{22}Ne	21.991 383	9.22%	
11	Sodium	22	^{22}Na	21.994 434	β^{+}	2.602 y
		23	^{23}Na	22.989 767	100%	
		24	^{24}Na	23.990 961	β^{-}	14.96 h

Table A9 Atomic Masses and Decay

Atomic number, Z	Name	Atomic Mass Number, A	Symbol	Atomic Mass (u)	Percent Abundance or Decay Mode	Half-life, $t_{1/2}$
12	Magnesium	24	^{24}Mg	23.985 042	78.99%	
13	Aluminum	27	^{27}Al	26.981 539	100%	
14	Silicon	28	^{28}Si	27.976 927	92.23%	2.62h
		31	^{31}Si	30.975 362	β^-	
15	Phosphorus	31	^{31}P	30.973 762	100%	
		32	^{32}P	31.973 907	β^-	14.28 d
16	Sulfur	32	^{32}S	31.972 070	95.02%	
		35	^{35}S	34.969 031	β^-	87.4 d
17	Chlorine	35	^{35}Cl	34.968 852	75.77%	
		37	^{37}Cl	36.965 903	24.23%	
18	Argon	40	^{40}Ar	39.962 384	99.60%	
19	Potassium	39	^{39}K	38.963 707	93.26%	
		40	^{40}K	39.963 999	0.0117%, EC, β^-	1.28×10^9 y
20	Calcium	40	^{40}Ca	39.962 591	96.94%	
21	Scandium	45	^{45}Sc	44.955 910	100%	
22	Titanium	48	^{48}Ti	47.947 947	73.8%	
23	Vanadium	51	^{51}V	50.943 962	99.75%	
24	Chromium	52	^{52}Cr	51.940 509	83.79%	
25	Manganese	55	^{55}Mn	54.938 047	100%	
26	Iron	56	^{56}Fe	55.934 939	91.72%	
27	Cobalt	59	^{59}Co	58.933 198	100%	
		60	^{60}Co	59.933 819	β^-	5.271 y
28	Nickel	58	^{58}Ni	57.935 346	68.27%	

Table A9 Atomic Masses and Decay

Atomic number, Z	Name	Atomic Mass Number, A	Symbol	Atomic Mass (u)	Percent Abundance or Decay Mode	Half-life, $t_{1/2}$
		60	^{60}Ni	59.930 788	26.10%	
29	Copper	63	^{63}Cu	62.939 598	69.17%	
			^{65}Cu	64.927 793	30.83%	
30	Zinc	64	^{64}Zn	63.929 145	48.6%	
		66	^{66}Zn	65.926 034	27.9%	
31	Gallium	69	^{69}Ga	68.925 580	60.1%	
32	Germanium	72	^{72}Ge	71.922 079	27.4%	
		74	^{74}Ge	73.921 177	36.5%	
33	Arsenic	75	^{75}As	74.921 594	100%	
34	Selenium	80	^{80}Se	79.916 520	49.7%	
35	Bromine	79	^{79}Br	78.918 336	50.69%	
36	Krypton	84	^{84}Kr	83.911 507	57.0%	
37	Rubidium	85	^{85}Rb	84.911 794	72.17%	
38	Strontium	86	^{86}Sr	85.909 267	9.86%	
		88	^{88}Sr	87.905 619	82.58%	
		90	^{90}Sr	89.907 738	β^-	28.8 y
39	Yttrium	89	^{89}Y	88.905 849	100%	
		90	^{90}Y	89.907 152	β^-	64.1 h
40	Zirconium	90	^{90}Zr	89.904 703	51.45%	
41	Niobium	93	^{93}Nb	92.906 377	100%	
42	Molybdenum	98	^{98}Mo	97.905 406	24.13%	
43	Technetium	98	^{98}Tc	97.907 215	β^-	4.2×10^6 y
44	Ruthenium	102	^{102}Ru	101.904 348	31.6%	

Table A9 Atomic Masses and Decay

Atomic number, Z	Name	Atomic Mass Number, A	Symbol	Atomic Mass (u)	Percent Abundance or Decay Mode	Half-life, $t_{1/2}$
45	Rhodium	103	^{103}Rh	102.905 500	100%	
46	Palladium	106	^{106}Pd	105.903 478	27.33%	
47	Silver	107	^{107}Ag	106.905 092	51.84%	
		109	^{109}Ag	108.904 757	48.16%	
48	Cadmium	114	^{114}Cd	113.903 357	28.73%	
49	Indium	115	^{115}In	114.903 880	95.7%, β^-	4.4×10^{14} y
50	Tin	120	^{120}Sn	119.902 200	32.59%	
51	Antimony	121	^{121}Sb	120.903 821	57.3%	
52	Tellurium	130	^{130}Te	129.906 229	33.8%, β^-	2.5×10^{21} y
53	Iodine	127	^{127}I	126.904 473	100%	
		131	^{131}I	130.906 114	β^-	8.040 d
54	Xenon	132	^{132}Xe	131.904 144	26.9%	
		136	^{136}Xe	135.907 214	8.9%	
55	Cesium	133	^{133}Cs	132.905 429	100%	
		134	^{134}Cs	133.906 696	EC, β^-	2.06 y
56	Barium	137	^{137}Ba	136.905 812	11.23%	
		138	^{138}Ba	137.905 232	71.70%	
57	Lanthanum	139	^{139}La	138.906 346	99.91%	
58	Cerium	140	^{140}Ce	139.905 433	88.48%	
59	Praseodymium	141	^{141}Pr	140.907 647	100%	
60	Neodymium	142	^{142}Nd	141.907 719	27.13%	
61	Promethium	145	^{145}Pm	144.912 743	EC, α	17.7 y
62	Samarium	152	^{152}Sm	151.919 729	26.7%	

Table A9 Atomic Masses and Decay

Atomic number, Z	Name	Atomic Mass Number, A	Symbol	Atomic Mass (u)	Percent Abundance or Decay Mode	Half-life, $t_{1/2}$
63	Europium	153	^{153}Eu	152.921 225	52.2%	
64	Gadolinium	158	^{158}Gd	157.924 099	24.84%	
65	Terbium	159	^{159}Tb	158.925 342	100%	
66	Dysprosium	164	^{164}Dy	163.929 171	28.2%	
67	Holmium	165	^{165}Ho	164.930 319	100%	
68	Erbium	166	^{166}Ho	165.930 290	33.6%	
69	Thulium	169	^{169}Tm	168.934 212	100%	
70	Ytterbium	174	^{174}Yb	173.938 859	31.8%	
71	Lutecium	175	^{175}Lu	174.940 770	97.41%	
72	Hafnium	180	^{180}Hf	179.946 545	35.10%	
73	Tantalum	181	^{181}Ta	180.947 992	99.98%	
74	Tungsten	184	^{184}W	183.950 928	30.67%	
75	Rhenium	187	^{187}Re	186.955 744	62.6%, β^-	4.6×10^{10}y
76	Osmium	191	^{191}Os	190.960 920	β^-	15.4 d
		192	^{192}Os	191.961 467	41.0%	
77	Iridium	191	^{191}Ir	190.960 584	37.3%	
		193	^{193}Ir	192.962 917	62.7%	
78	Platinum	195	^{195}Pt	194.964 766	33.8%	
79	Gold	197	^{197}Au	196.966 543	100%	
		198	^{198}Au	197.968 217	β^-	2.696 d
80	Mercury	199	^{199}Hg	198.968 253	16.87%	
		202	^{202}Hg	201.970 617	29.86%	
81	Thallium	205	^{205}Tl	204.974 401	70.48%	

Table A9 Atomic Masses and Decay

Atomic number, Z	Name	Atomic Mass Number, A	Symbol	Atomic Mass (u)	Percent Abundance or Decay Mode	Half-life, $t_{1/2}$
82	Lead	206	^{206}Pb	205.974 440	24.1%	
		207	^{207}Pb	206.975 872	22.1%	
		208	^{208}Pb	207.976 627	52.4%	
		210	^{210}Pb	209.984 163	α, β^-	22.3 y
		211	^{211}Pb	210.988 735	β^-	36.1 min
		212	^{212}Pb	211.991 871	β^-	10.64 h
83	Bismuth	209	^{209}Bi	208.980 374	100%	
		211	^{211}Bi	210.987 255	α, β^-	2.14 min
84	Polonium	210	^{210}Po	209.982 848	α	138.38 d
85	Astatine	218	^{218}At	218.008 684	α, β^-	1.6 s
86	Radon	222	^{222}Rn	222.017 570	α	3.82 d
87	Francium 2	223	^{223}Fr	223.019 733	α, β^-	21.8 min
88	Radium	226	^{226}Ra	226.025 402	α	1.60×10^3 y
89	Actinium	227	^{227}Ac	227.027 750	α, β^-	21.8 y
90	Thorium	228	^{228}Th	228.028 715	α	1.91 y
		232	^{232}Th	232.038 054	100%, α	1.41×10^{10} y
91	Protactinium	231	^{231}Pa	231.035 880	α	3.28×10^4 y
92	Uranium	233	^{233}U	233.039 628	α	1.59×10^3 y
		235	^{235}U	235.043 924	0.720%, α	7.04×10^8 y
		236	^{236}U	236.045 562	α	2.34×10^7 y

Table A9 Atomic Masses and Decay

Atomic number, Z	Name	Atomic Mass Number, A	Symbol	Atomic Mass (u)	Percent Abundance or Decay Mode	Half-life, $t_{1/2}$
		238	^{238}U	238.050 784	99.2745%, α	4.47 × 10^9 y
		239	^{239}U	239.054 289	$β^-$	23.5 min
93	Neptunium	239	^{239}Np	239.052 933	$β^-$	2.355 d
94	Plutonium	239	^{239}Pu	239.052 157	α	2.41 × 10^4 y
95	Americium	243	^{243}Am	243.061 375	α, fission	7.37 × 10^3 y
96	Curium	245	^{245}Cm	245.065 483	α	8.50 × 10^3 y
97	Berkelium	245	^{247}Bk	247.070 300	α	1.38 × 10^3 y
98	Californium	249	^{249}Cf	249.074 844	α	351 y
99	Einsteinium	254	^{254}Es	254.088 019	α, $β^-$	276 d
100	Fermium	253	^{253}Fm	253.085 173	EC, α	3.00 d
101	Mendelevium	255	^{255}Md	255.091 081	EC, α	27 min
102	Nobelium	255	^{255}No	255.093 260	EC, α	3.1 min
103	Lawrencium	257	^{257}Lr	257.099 480	EC, α	0.646 s
104	Rutherfordium	261	^{261}Rf	261.108 690	α	1.08 mim
105	Dubnium	262	^{262}Db	262.113 760	α, fission	34 s
106	Seaborgium	263	^{263}Sg	263.11 86	α, fission	0.8 s
107	Bohrium	262	^{262}Bh	262.123 1	α	0.102 s
108	Hassium	264	^{264}Hs	264.128 5	α	0.08 ms
108	Meitnerium	266	^{266}Mt	266.137 8	α	3.4 ms

Table A9 Atomic Masses and Decay

Isotope	$t_{1/2}$	Decay Mode	Energy(MeV)	Percent		T-Ray Energy(MeV)	Percent
^{3}H	12.33 y	β^-	0.0186	100%			
^{14}C	5730 y	β^-	0.156	100%			
^{13}N	9.96 min	β^+	1.20	100%			
^{22}Na	2.602 y	β^+	1.20	90%	γ	1.27	100%
^{32}P	14.28 d	β^-	1.71	100%			
^{35}S	87.4 d	β^-	0.167	100%			
^{36}Ci	3.00 × 105 y	β^-	0.710	100%			
^{40}K	1.28 × 109 y	β^-	1.31	89%			
^{43}K	22.3 h	β^-	0.827	87%	γs	0.373	87%
						0.618	87%
^{45}Ca	165 d	β^-	0.257	100%			
^{51}Cr	27.70 d	EC			γ	0.320	10%
^{52}Mn	5.59d	β^+	3.69	28%	γ s	1.33	28%
						1.43	28%
^{52}Fe	8.27 h	β^+	1.80	43%		0.169	43%
						0.378	43%
^{59}Fe	44.6 d	β^- s	0.273	45%	γ s	1.10	57%
			0.466	55%		1.29	43%
^{60}Co	5.271 y	β^-	0.318	100%	γ s	1.17	100%
						1.33	100%
^{65}Zn	244.1 d	EC			γ	1.12	51%
^{67}Ga	78.3 h	EC			γ s	0.0933	70%
						0.185	35%
						0.300	19%

Table A10 Selected Radioactive Isotopes

Isotope	^{t}1/2	Decay Mode	Energy(MeV)	Percent		T-Ray Energy(MeV)	Percent
						others	
^{75}Se	118.5 d	EC			γ s	0.121	20%
						0.136	65%
						0.265	68%
						0.280	20%
						others	
^{86}Rb	18.8 d	β⁻ s	0.69	9%	γ	1.08	9%
			1.77	91%			
^{85}Sr	64.8 d	EC			γ	0.514 1	100%
^{90}Sr	28.8 y	β⁻	0.546	100%			
^{90}Y	64.1 h	β⁻	2.28	100%			
^{99m}Tc	6.02 h	IT			γ	0.142	100%
^{113}mIn	99.5 ^{m}in	IT			γ	0.392	100%
^{123}I	13.0 h	EC			γ	0.159	≈100%
^{131}I	8.040 d	β⁻ s	0.248	7%	γ s	0.364	85%
			0.607	93%		others	
			others				
^{129}Cs	32.3 h	EC			γ s	0.0400	35%
						0.372	32%
						0.411	25%
						others	
^{137}Cs	30.17 y	β⁻ s	0.511	95%	γ	0.662	95%
			1.17	5%			
^{140}Ba	12.79 d	β⁻	1.035	≈100%	γ s	0.030	25%

Table A10 Selected Radioactive Isotopes

Isotope	t1/2	Decay Mode	Energy(MeV)	Percent		T-Ray Energy(MeV)	Percent
						0.044	65%
						0.537	24%
						others	
^{198}Au	2.696 d	β^-	1.161	≈100%	γ	0.412	≈100%
^{197}Hg	64.1 h	EC			γ	0.0733	100%
^{210}Po	138.38 d	α	5.41	100%			
^{226}Ra	1.60 × 103 y	αs	4.68	5%	γ	0.186 1	100%
			4.87	95%			
^{235}U	7.038 × 108 y	α	4.68	≈100%	γ s	Numerous	<0.400%
^{238}U	4.468 × 109 y	αs	4.22	23%	γ	0.050	23%
			4.27	77%			
^{237}Np	2.14 × 106 y	αs	numerous		γ s	numerous	<0.250%
			4.96 (max.)				
^{239}Pu	2.41 × 104 y	αs	5.19	11%	γ s	7.5 × 10-5	73%
			5.23	15%		0.013	15%
			5.24	73%		0.052	15%
						others	
^{243}Am	7.37 × 103 y	αs	Max. 5.44		γ s	0.075	
			5.37	88%		others	
			5.32	11%			
			others				

Table A10 Selected Radioactive Isotopes

Symbol	Meaning	Best Value	Approximate Value
m_e	Electron mass	$9.10938291(40) \times 10^{-31}$ kg	9.11×10^{-31} kg

Table A11 Submicroscopic masses

Symbol	Meaning	Best Value	Approximate Value
m_p	Proton mass	$1.672621777(74) \times 10^{-27}$ kg	1.6726×10^{-27} kg
m_n	Neutron mass	$1.674927351(74) \times 10^{-27}$ kg	1.6749×10^{-27} kg
u	Atomic mass unit	$1.660538921(73) \times 10^{-27}$ kg	1.6605×10^{-27} kg

Table A11 Submicroscopic masses

Substance	ρ(kg/m^3)	Substance	ρ(kg/m^3)
Air	1.29	Iron	7.86×10^3
Air (at 20°C and Atmospheric pressure)	1.20	Lead	11.3×10^3
Aluminum	2.70×10^3	Mercury	13.6×10^3
Benzene	0.879×10^3	Nitrogen gas	1.25
Brass	8.4×10^3	Oak	0.710×10^3
Copper	8.92×10^3	Osmium	22.6×10^3
Ethyl alcohol	0.806×10^3	Oxygen gas	1.43
Fresh water	1.00×10^3	Pine	0.373×10^3
Glycerin	1.26×10^3	Platinum	21.4×10^3
Gold	1.93×10^3	Seawater	1.03×10^3
Helium gas	1.79×10^{-1}	Silver	10.5×10^3
Hydrogen gas	8.99×10^{-2}	Tin	7.30×10^3
Ice	0.917×10^3	Uranium	18.7×10^3

Table A12 Densities of common substances (including water at various temperatures)

Substance	Specific Heat (J/kg · °C)	Substance	Specific Heat (J/kg · °C)
Elemental solids		*Other solids*	
Aluminum	900	Brass	380
Beryllium	1830	Glass	837
Cadmium	230	Ice (−5 °C)	2090

Table A13 Specific heats of common substances

Substance	Specific Heat (J/kg · °C)	Substance	Specific Heat (J/kg · °C)
Copper	387	Marble	860
Germanium	322	Wood	1700
Gold	129	*Liquids*	
Iron	448	Alcohol (ethyl)	2400
Lead	128	Mercury	140
Silicon	703	Water (15 °C)	4186
Silver	234	*Gas*	
		Steam (100 °C)	2010
Note: To convert values to units of cal/g · °C, divide by 4186			

Table A13 Specific heats of common substances

Substance	Melting Point (°C)	Latent Heat of Fusion (J/kg)	Boiling Point (°C)	Latent Heat of Vaporization (J/kg)
Helium	−272.2	5.23×10^3	−268.93	2.09×10^4
Oxygen	−218.79	1.38×10^4	−182.97	2.13×10^5
Nitrogen	−209.97	2.55×10^4	−195.81	2.01×10^5
Ethyl Alcohol	−114	1.04×10^5	78	8.54×10^5
Water	0.00	3.33×10^5	100.00	2.26×10^6
Sulfur	119	3.81×10^4	444.60	2.90×10^5
Lead	327.3	3.97×10^5	1750	8.70×10^5
Aluminum	660	3.97×10^5	2516	1.05×10^7
Silver	960.80	8.82×10^4	2162	2.33×10^6
Gold	1063.00	6.44×10^4	2856	1.58×10^6
Copper	1083	1.34×10^5	2562	5.06×10^6

Table A14 Heats of fusion and vaporization for common substances

Materials (Solids)	Average Linear Expansion Coefficient (α)(°C)$^{-1}$	Material (Liquids and Gases)	Average Volume Expansion Coefficient (B)(°C)$^{-1}$
Aluminum	24×10^{-6}	Acetone	1.5×10^{-4}
Brass and Bronze	19×10^{-6}	Alcohol, ethyl	1.12×10^{-4}
Concrete	12×10^{-6}	Benzene	1.24×10^{-4}
Copper	17×10^{-6}	Gasoline	9.6×10^{-4}
Glass (ordinary)	9×10^{-6}	Glycerin	4.85×10^{-4}
Glass (Pyrex)	3.2×10^{-6}	Mercury	1.82×10^{-4}
Invar (Ni-Fe alloy)	1.3×10^{-6}	Turpentine	9.0×10^{-4}
Lead	29×10^{-6}	Air* at 0°C	3.67×10^{-3}
Steel	13×10^{-6}	Helium*	3.665×10^{-3}

* The values given here assume the gases undergo expansion at constant pressure. However, the expansion of gases depends on the pressure applied to the gas. Therefore, gases do not have a specific value for the volume expansion coefficient.

Table A15 Coefficients of thermal expansion for common substances

Medium	v(m/s)	Medium	v(m/s)	Medium	v(m/s)
Gases		Liquids at 25°C		Solids*	
Hydrogen	1286	Glycerol	1904	Pyrex glass	5640
Helium	972	Seawater	1533	Iron	5950
Air	343	Water	1493	Aluminum	5100
Air	331	Mercury	1450	Brass	4700
Oxygen	317	Kerosene	1324	Copper	3560
		Methyl Alcohol	1143	Gold	3240
		Carbon tetrachloride	926	Lucite	2680
				Lead	1322
				Rubber	1600

Table A16 Speed of sound in various substances

Medium	*v*(m/s)	Medium	*v*(m/s)	Medium	*v*(m/s)

*Values given here are for propagation of longitudinal waves in bulk media. However, speeds for longitudinal waves in thin rods are slower, and speeds of transverse waves in bulk are even slower.

Table A16 Speed of sound in various substances

Source of Sound	*B(dB)*
Nearby jet airplane	150
Jackhammer machine gun	130
Siren; rock concert	120
Subway; power lawn mower	100
Busy traffic	80
Vacuum cleaner	70
Normal Conversation	60
Mosquito buzzing	40
whisper	30
Rustling leaves	10
Threshold of hearing	0

Table A17 Conversion of sound intensity to decibel level

Wavelength Range (nm)	Color Description
400-430	Violet
430-485	Blue
485-560	Green
560-590	Yellow
590-625	Orange
625-700	Red

Table A18 Wavelengths of visible light

Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		Liquids at 20°C	
Cubic zirconia	2.15	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Flourite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473
Glass, crown	1.52	Water	1.333
Glass, flint	1.66		
Ice (H_2O)	1.309	Gases at 0°C, 1 *atm*	
Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

Note: These values assume that light has a wavelength of 589 nm in vacuum.

Table A19 Indices of refraction

Hoop or thin cylindrical shell	$I_{CM} = MR^2$
Hollow cylinder	$I_{CM} = \frac{1}{2}M(R_1^2 + R_2^2)$
Solid cylinder or disk	$I_{CM} = \frac{1}{2}MR^2$
Rectangular plane	$I_{CM} = \frac{1}{12}M(a^2 + b^2)$
Long, thin rod with rotation axis through center	$I_{CM} = \frac{1}{12}ML^2$
Long, thin rod with rotation axis through end	$I_{CM} = \frac{1}{3}ML^2$
Solid sphere	$I_{CM} = \frac{2}{5}MR^2$
Thin spherical shell	$I_{CM} = \frac{2}{3}MR^2$

Table A20 Moments of inertia for different shapes

	μ_s	μ_k
Rubber on dry concrete	1.0	0.8

Table A21 Coefficients of friction for common objects on other objects

	μ_s	μ_k
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Glass on glass	0.94	0.4
Copper on steel	0.53	0.36
Wood on wood	0.25-0.5	0.2
Waxed wood on wet snow	0.14	0.1
Waxed wood on dry snow	0.1	0.04
Metal on metal (lubricated)	0.15	0.06
Teflon on Teflon	0.04	0.04
Ice on ice	0.1	0.03
Synovial joints in humans	0.01	0.003

Note: All values are approximate. In some cases, the coefficient of friction can exceed 1.0.

Table A21 Coefficients of friction for common objects on other objects

Material	Dielectric Constant κ	Dielectric Strength* (10^6V/m)
Air (dry)	1.000 59	3
Bakelite	4.9	24
Fused quartz	4.3	8
Mylar	3.2	7
Neoprene rubber	6.7	12
Nylon	3.4	14
Paper	3.7	16
Paraffin-impregnated paper	3.5	11
Polystyrene	2.56	24
Polyvinyl chloride	3.4	40
Porcelain	6	8

Table A22 Dielectric constants

Material	Dielectric Constant κ	Dielectric Strength* (10^6V/m)
Pyrex glass	5.6	14
Silicone oil	2.5	15
Strontium titanate	233	8
Teflon	2.1	60
Vacuum	1.000 00	∞
Water	80	3

Table A22 Dielectric constants

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