Chapter 26 Electromagnetism

What You'll Learn

- You will learn how combined electric and magnetic fields can be used to determine the masses of electrons, atoms, and molecules.
- You will explain how electromagnetic waves are created, travel through space, and are detected.

Why It's Important

Many electromagnetic waves—from radio and television waves, to visible light, microwaves, and X rays—play vital roles in our lives.

Parabolic Receivers
This parabolic dish antenna is designed to receive radio waves from satellites orbiting hundreds of kilometers above Earth's surface and objects well beyond the solar system.

Think About This ▶

A parabolic dish gets its name from the shape of its reflecting surface—a parabola. Why are parabolic dish antennas well suited for receiving weak television signals?

Physics Online
physicspp.com

Rick England/Getty Images

LAUNCH Lab

From where do radio stations broadcast?

Question

Radio signals are electromagnetic waves. How far away are the transmitters that are used to broadcast the radio station signals that you can tune in on the AM band?

Procedure

1. The AM radio band ranges from 540 kHz to 1690 kHz. Make a data table with columns for *Frequency (kHz), Station Call Sign, Signal Strength, Location, and Distance (km).*
2. Turn on the radio, adjust it to 540 kHz, and set the volume to a moderate level.
3. **Collect and Organize Data** Slowly adjust the frequency upward until you hear a radio station whose broadcast you can clearly understand. Listen to the broadcast for a short time to hear if the station identifies its call sign. Record the station's frequency, signal strength (strong, medium, or weak), and call sign in your data table.
4. Repeat step 3 until you have reached the upper end of the AM radio band, 1690 kHz.
5. Determine where each station broadcasts its signal from. Record the city each station broadcasts from in your data table.
6. **Measure in SI** Using maps, locate the city from which each radio station broadcasts. Determine the distance to each transmitter and record the value in your data table.

Analysis

How far away was the farthest radio station broadcast? Does the distance from the transmitter affect the station's signal strength?

Critical Thinking

Changing the position of the antenna often affects a station's signal strength. What does this imply about the nature of radio waves?

26.1 Interactions of Electric and Magnetic Fields and Matter

Although you may not know what the terms stand for, you have probably heard of shortwave radio, microwaves, and VHF and UHF television signals. Each of these terms is used to describe one of the many types of electromagnetic waves that are broadcast through the air to provide you with radio, television, and other forms of communication. All of these waves consist of electric and magnetic fields propagating through space.

The key to understanding how these waves behave is understanding the nature of the electron. Why? Because electromagnetic waves are produced by accelerating electrons—the electrons' charge produces electric fields and the electrons' motion produces magnetic fields. Furthermore, the waves are broadcast and received by antennas, devices made of matter that also contains electrons. Thus, the logical first step in understanding how electromagnetic waves are produced, propagated, received, and used for so many devices is to learn about the properties of the electron.

▶ Objectives

- **Describe** the operation of a cathode-ray tube.
- **Solve** problems involving the interaction of charged particles with the electric and magnetic fields in cathode-ray tubes and mass spectrometers.
- **Explain** how a mass spectrometer separates ions of different masses.

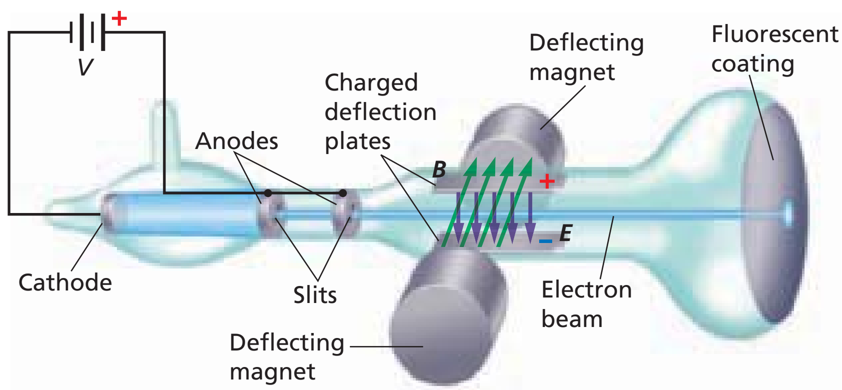
▶ Vocabulary

isotope
mass spectrometer

Mass of an Electron

How do you determine the mass of something that cannot be seen with the unaided eye and whose mass is so small that it cannot be measured even by the most sensitive scale? Such was the challenge—that of determining the mass of an electron—facing physicists in the late 1800s. The solution required a series of discoveries. The first piece of the puzzle came from Robert Millikan. As described in Chapter 21, Millikan balanced charged oil droplets in an electric field and was able to determine the charge, q, of an electron (1.602×10^{-19} C). Next, British physicist J. J. Thomson was able to determine the charge-to-mass ratio, q/m, of an electron. Knowing both the charge-to-mass ratio, q/m, and the charge of an electron, q, Thomson was able to calculate the mass of an electron.

Thomson's experiments with electrons In 1897, J. J. Thomson performed the first experimental measurement of the charge-to-mass ratio of an electron. Thomson used a cathode-ray tube, a device that generates a stream of electrons. **Figure 26-1** shows the setup used in the experiment. In order to minimize collisions between the electron beam and the molecules in the air, Thomson removed virtually all of the air from within the glass tube.



■ **Figure 26-1** The charge-to-mass ratio of an electron was first measured with the Thomson adaptation of a cathode-ray tube. The electromagnets and charged deflection plates both are used to alter the path of the electron beam.

CLICK HERE

Concepts In Motion

Interactive Figure To see an animation on Thomson's experiments with electrons, visit physicspp.com.

Inside the cathode-ray tube, an electric field is produced by a large potential difference between the cathode and anode. Electrons are emitted from the cathode and are accelerated toward the anodes by the electric field. Some of the electrons pass through slits in the anodes, forming a narrow beam. When the electrons reach the end of the tube they strike a fluorescent coating, causing it to glow.

Thomson used electric and magnetic fields to exert force on and deflect the electron beam as it passed through the tube. The electric field, which was produced by charged parallel plates, was oriented perpendicular to the beam. The electric field (of strength E) produced a force (equal to qE) that acted on the electrons and deflected them upward, toward the positive plate. The magnetic field was produced by two electromagnets and was oriented at right angles to both the beam and the electric field. Recall from Chapter 24 that the force exerted by a magnetic field is perpendicular to the field and to the direction of motion of the electrons. Thus, the magnetic field (of strength B) produced a force (equal to Bqv, where v is the electron velocity) that acted on the electrons and deflected them downward.

The electric and magnetic fields could be adjusted until the beam of electrons followed a straight, or undeflected, path. When this occurred, the forces due to the two fields were equal in magnitude and opposite in direction. Mathematically, this can be represented as follows:

$$Bqv = Eq$$

Solving this equation for v yields the following expression:

$$v = \frac{Eq}{Bq} = \frac{E}{B}$$

This equation shows that the forces are balanced only for electrons that have a specific velocity, v. If the electric field is turned off, only the force due to the magnetic field remains. The magnetic force is perpendicular to the direction of motion of the electrons, causing them to undergo centripetal (center-directed) acceleration. The accelerating electrons follow a circular path of radius r. Using Newton's second law of motion, the following equation can be written to describe the electron's path:

$$Bqv = \frac{mv^2}{r}$$

Solving for q/m results in the following equation.

Charge-to-Mass Ratio in a Thomson Tube $\frac{q}{m} = \frac{v}{Br}$

In a Thomson tube, the ratio of an electron's charge to its mass is equal to the ratio of the electron's velocity divided by the product of the magnetic field strength and the radius of the electron's circular path.

Thomson calculated the straight trajectory velocity, v, using measured values of E and B. Next, he measured the distance between the spot formed by the undeflected beam and the spot formed when the magnetic field acted on the beam. Using this distance, he calculated the radius of the electron's circular path, r. Knowing the value of r, Thomson was able to calculate q/m. By averaging many experimental trials, he determined that $q/m = 1.759\times10^{11}$ C/kg. Using this value for q/m and the known value of q, the mass of the electron (m) was calculated.

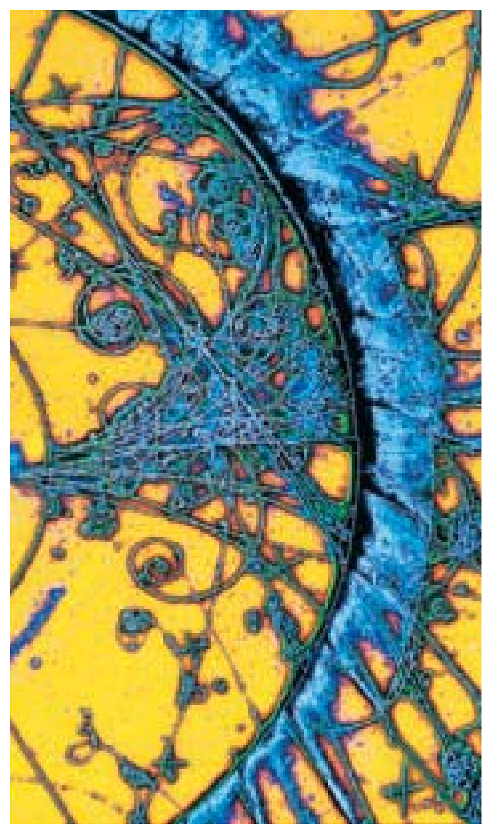
$$m = \frac{q}{q/m} = \frac{1.602\times10^{-19}\ \text{C}}{1.759\times10^{11}\ \text{C/kg}} = 9.107\times10^{-31}\ \text{kg}$$

$$m \cong 9.11\times10^{-31}\ \text{kg}$$

Thomson's experiments with protons Thomson also used his cathode-ray test apparatus to determine the charge-to-mass ratio for positive ions. He took advantage of the fact that positively charged particles undergo the opposite deflection experienced by electrons moving through an electric or magnetic field. The differing deflection of electrons and positive ions can be seen in **Figure 26-2.**

To accelerate positively charged particles into the deflection region, Thomson reversed the direction of the electric field between the cathode and anodes. He also added a small amount of hydrogen gas to the tube. The electric field pulled electrons off the hydrogen atoms, changing the atoms into positive ions. These positive hydrogen ions, or protons, were then accelerated through a tiny slit in the anode. The resulting proton beam passed through electric and magnetic fields on its way toward the end of the tube.

Figure 26-2 This photograph shows the circular tracks of electrons (e^-) and positrons (e^+) moving through the magnetic field in a bubble chamber, a type of particle detector used in the early years of high-energy physics. Electrons and positrons curve in opposite directions.



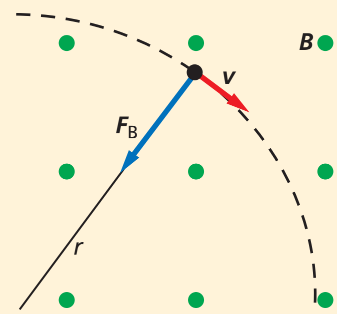
Using this technique, the mass of a proton was determined in the same manner as was the mass of the electron. The mass of a proton was found to be 1.67×10^{-27} kg. Thomson went on to use this technique to determine the masses of heavier ions produced when electrons were stripped from gases, such as helium, neon, and argon.

▶ EXAMPLE Problem 1

Path Radius An electron with a mass of 9.11×10^{-31} kg moves through a cathode-ray tube at 2.0×10^{5} m/s perpendicular to a magnetic field of 3.5×10^{-2} T. The electric field is turned off. What is the radius of the circular path that is followed by the electron?

1 Analyze and Sketch the Problem

- Draw the path of the electron and label the velocity, v.
- Sketch the magnetic field perpendicular to the velocity.
- Diagram the force acting on the electron. Add the radius of the electron's path to your sketch.



Known:	Unknown:
$v = 2.0\times10^{5}$ m/s	$r = ?$
$B = 3.5\times10^{-2}$ T	
$m = 9.11\times10^{-31}$ kg	
$q = 1.602\times10^{-19}$ C	

2 Solve for the Unknown

Use Newton's second law of motion to describe an electron in a cathode-ray tube subjected to a magnetic field.

Math Handbook
Operations with Scientific Notation
pages 842–843

$$Bqv = \frac{mv^2}{r}$$

$$r = \frac{mv}{Bq}$$

$$= \frac{(9.11\times10^{-31}\text{ kg})(2.0\times10^{5}\text{ m/s})}{(3.5\times10^{-2}\text{ T})(1.602\times10^{-19}\text{ C})}$$

Substitute $m = 9.11\times10^{-31}$ kg, $v = 2.0\times10^{5}$ m/s, $B = 3.5\times10^{-2}$ T, $q = 1.602\times10^{-19}$ C

$$= 3.3\times10^{-5}\text{ m}$$

3 Evaluate the Answer

- **Are the units correct?** The radius of the circular path is a length measurement, given in units of meters.

▶ PRACTICE Problems

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

Assume that all charged particles move perpendicular to a uniform magnetic field.

1. A proton moves at a speed of 7.5×10^{3} m/s as it passes through a magnetic field of 0.60 T. Find the radius of the circular path. Note that the charge carried by the proton is equal to that of the electron, but is positive.

2. Electrons move through a magnetic field of 6.0×10^{-2} T balanced by an electric field of 3.0×10^{3} N/C. What is the speed of the electrons?

3. Calculate the radius of the circular path that the electrons in problem 2 follow in the absence of the electric field.

4. Protons passing without deflection through a magnetic field of 0.60 T are balanced by an electric field of 4.5×10^{3} N/C. What is the speed of the moving protons?

The Mass Spectrometer

An interesting thing happened when Thomson put neon gas into the cathode-ray tube—he observed two glowing dots on the screen instead of one. Each dot corresponded to a unique charge-to-mass ratio; that is, he was able to calculate two different values for q/m. Thomson concluded that different atoms of the same element could have identical chemical properties, but have different masses. Each of the differing forms of the same atom, with the same chemical properties but different masses, is an **isotope.**

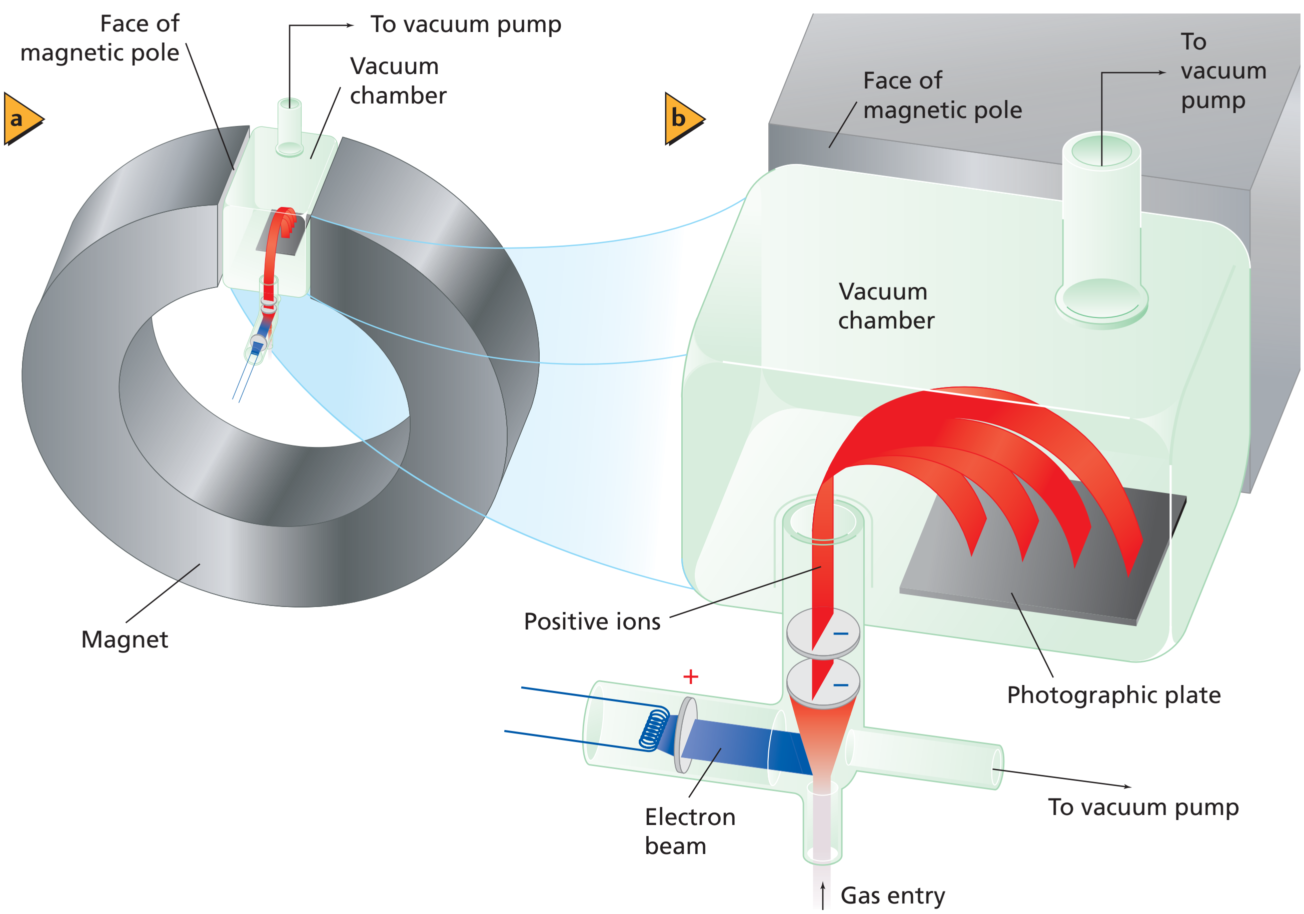
A device similar to Thomson's cathode-ray tube that is commonly used to study isotopes is the **mass spectrometer.** The mass spectrometer is able to precisely measure the charge-to-mass ratios of positive ions. From the charge-to-mass ratio, the mass of each isotope can be calculated. The material under investigation is called the ion source, as it is used to produce the positive ions. The ion source must either be a gas or a material that can be heated to form a vapor. The positive ions are formed when accelerated electrons strike the gas or vapor atoms. The collisions knock electrons off the atoms, forming positive ions. A potential difference, V, between the electrodes produces an electric field that is used to accelerate the ions. **Figure 26-3** shows one type of mass spectrometer.

CLICK HERE

Concepts In MOtion

Interactive Figure To see an animation on a mass spectrometer, visit physicspp.com.

■ **Figure 26-3** The mass spectrometer is used to analyze isotopes of an element. Inside the spectrometer, a magnet causes the positive ions in a vacuum chamber to be deflected according to their mass **(a).** In the vacuum chamber, the process is recorded on a photographic plate or a solid-state detector **(b).**



To select ions with a specific velocity, the ions first are made to pass through electric and magnetic deflecting fields, as in Thomson's cathode-ray tube. Ions that pass undeflected through these two fields then move into a region that is subject only to a uniform magnetic field. There, the ions follow a circular path. The radii of the paths can be used to determine the charge-to-mass ratios of the ions. The path radius, r, for an ion can be calculated from Newton's second law of motion.

$$Bqv = \frac{mv^2}{r}$$

Solving for r yields the following equation:

$$r = \frac{mv}{qB}$$

The velocity of an undeflected ion can be calculated from the equation for the kinetic energy of ions accelerated from rest, through a known potential difference, V.

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

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

Substituting this expression for v in the equation $r = mv/qB$ gives the radius of the circular path.

$$r = \frac{mv}{qB}$$

$$= \frac{m}{qB}\sqrt{\frac{2qV}{m}}$$

$$= \frac{1}{B}\sqrt{\frac{2Vm}{q}}$$

Simplifying this equation by multiplying both sides by B yields the following:

$$Br = \sqrt{\frac{2mV}{q}}$$

This equation can be used to determine the charge-to-mass ratio of an ion.

Charge-to-Mass Ratio of an Ion in a Mass Spectrometer

$$\frac{q}{m} = \frac{2V}{B^2r^2}$$

In a mass spectrometer, the ratio of an ion's charge to its mass is equal to twice the potential difference divided by the product of the square of the magnetic field strength and the square of the radius of the ion's circular path.

As shown in Figure 26-3, in one type of mass spectrometer, the ions strike a plate of photographic film, where they leave a mark. The diameter of the curved path traveled by the ions in the vacuum chamber can be easily measured because it is the distance between the mark made on the film and the slit in the electrode. Therefore, the radius of the path, r, is half of this measured distance.

MINI LAB

Modeling a Mass Spectrometer

Make a ramp by placing a small ball of clay under one end of a grooved ruler. Place a 6-mm-diameter steel ball about halfway up the ramp and release it.

1. Observe the ball as it rolls down the ramp and along the table top.

2. Experiment with the location of a strong magnet near the path of the ball on the table top. Place the magnet close to the path so that it causes the ball's path to curve, but not so close that it causes the ball to collide with the magnet. Repeat step 1 as needed.

3. Predict what will happen to the ball's path when the ball is released from a higher or lower point on the ramp.

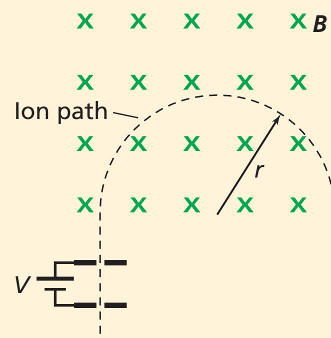
4. Test your prediction.

Analyze and Conclude

5. Explain if the observed results are consistent with those for a charged particle moving through a magnetic field.

▶ EXAMPLE Problem 2

Mass of a Neon Atom The operator of a mass spectrometer produces a beam of doubly ionized (2+) neon atoms. They first are accelerated by a potential difference of 34 V. Then, as the ions pass through a magnetic field of 0.050 T, the radius of their path is 53 mm. Determine the mass of the neon atom to the closest whole number of proton masses.



1 Analyze and Sketch the Problem

- Draw the circular path of the ions. Label the radius.
- Draw and label the potential difference between the electrodes.

	Known:	Unknown:
$V = 34$ V	$m_{\text{proton}} = 1.67\times10^{-27}$ kg	$m_{\text{neon}} = ?$
$B = 0.050$ T	$q = 2(1.60\times10^{-19}$ C$)$	$N_{\text{proton}} = ?$
$r = 0.053$ m	$= 3.20\times10^{-19}$ C	

2 Solve for the Unknown

Use the equation for the charge-to-mass ratio of an ion in a mass spectrometer.

$$\frac{q}{m_{\text{neon}}} = \frac{2V}{B^2r^2}$$

$$m_{\text{neon}} = \frac{qB^2r^2}{2V}$$

$$= \frac{(3.20\times10^{-19}\text{ C})(0.050\text{ T})^2(0.053\text{ m})^2}{2(34\text{ V})}$$

Substitute $q = 3.20\times10^{-19}$ C, $B = 0.050$ T, $r = 0.053$ m, and $V = 34$ V

$$= 3.3\times10^{-26}\text{ kg}$$

Divide the mass of neon by the mass of a proton to find the number of proton masses.

$$N_{\text{proton}} = \frac{m_{\text{neon}}}{m_{\text{proton}}} = \frac{3.3\times10^{-26}\text{ kg}}{1.67\times10^{-27}\text{ kg/proton}}$$

$$\cong 20\text{ protons}$$

3 Evaluate the Answer

- **Are the units correct?** Mass should be measured in grams or kilograms. The number of protons should not be represented by any units.
- **Is the magnitude realistic?** Neon has two isotopes, with masses of approximately 20 and 22 proton masses.

Physics Online

Personal Tutor For an online tutorial on the mass of an atom, visit physicspp.com.

▶ PRACTICE Problems

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

5. A beam of singly ionized (1+) oxygen atoms is sent through a mass spectrometer. The values are $B = 7.2\times10^{-2}$ T, $q = 1.60\times10^{-19}$ C, $r = 0.085$ m, and $V = 110$ V. Find the mass of an oxygen atom.

6. A mass spectrometer analyzes and gives data for a beam of doubly ionized (2+) argon atoms. The values are $q = 2(1.60\times10^{-19}$ C$)$, $B = 5.0\times10^{-2}$ T, $r = 0.106$ m, and $V = 66.0$ V. Find the mass of an argon atom.

7. A stream of singly ionized (1+) lithium atoms is not deflected as it passes through a magnetic field of 1.5×10^{-3} T that is perpendicular to an electric field of 6.0×10^{2} N/C. What is the speed of the lithium atoms as they pass through the two fields?

8. In Example Problem 2, the mass of a neon isotope is determined. Another neon isotope is found to have a mass of 22 proton masses. How far apart on the photographic film would these two isotopes land?

Chemistry Connection

Isotopic analysis The approximate spacing between marks on the film for an ionized chromium (Cr) sample is shown in **Figure 26-4.** The four distinct red marks indicate that a naturally occurring sample of chromium is composed of four isotopes. The width of the mark corresponds to the abundance of the isotope. Note that the isotope with a mass number of 52 is the most abundant isotope, and that the sum of the percentages for the four isotopes equals 100 percent. As you may recall from chemistry, the mass of each element listed in the periodic table is actually a weighted average of the masses of all of the stable isotopes of that element.

Note that all of the chromium ions that hit the film have the same charge. Their charge depends on how many electrons were removed from the neutral chromium atoms used as the ion source. Recall that the ions are formed when accelerated electrons are used to knock electrons off neutral atoms. After the first electron is removed, producing a singly ionized (1+) atom, more energy is required to remove the second electron and produce a double ionized (2+) atom. This additional energy can be provided by electrons that undergo a greater acceleration because they are subjected to a greater electric field. Thus, higher-energy accelerated electrons can produce both singly and doubly charged ions. In this way, the operator of the mass spectrometer can choose the charge on the ion to be studied.

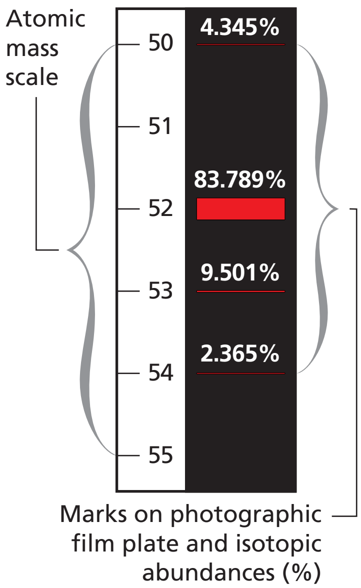


Figure 26-4 Mass spectrometers are widely used to determine the isotopic composition of an element. The above illustration shows the results of analyzing the marks left on a film plate by chromium isotopes.

Other applications Mass spectrometers have numerous applications. For example, a mass spectrometer can be used to "purify" a sample of uranium into its component isotopes. Rather than striking a detector to measure relative abundance, the separated isotopes are collected. The different isotopes are, in turn, used in varying applications. Mass spectrometers also are used to detect and identify trace amounts of molecules in a sample, an application extensively used in the environmental and forensic sciences. The device is so sensitive that researchers are able to separate ions with mass differences as small as one ten-thousandth of one percent and are able to identify the presence of a single molecule within a 10 billion-molecule sample.

26.1 Section Review

9. **Cathode-Ray Tube** Describe how a cathode-ray tube forms an electron beam.

10. **Magnetic Field** The radius of the circular path of an ion in a mass spectrometer is given by $r = (1/B)\sqrt{2Vm/q}$. Use this equation to explain how a mass spectrometer is able to separate ions of different masses.

11. **Magnetic Field** A modern mass spectrometer can analyze molecules having masses of hundreds of proton masses. If the singly charged ions of these molecules are produced using the same accelerating voltage, how would the mass spectrometer's magnetic field have to be changed for the ions to hit the film?

12. **Path Radius** A proton moves at a speed of 4.2×10^{4} m/s as it passes through a magnetic field of 1.20 T. Find the radius of the circular path.

13. **Mass** A beam of doubly ionized (2+) oxygen atoms is accelerated by a potential difference of 232 V. The oxygen then enters a magnetic field of 75 mT and follows a curved path with a radius of 8.3 cm. What is the mass of the oxygen atom?

14. **Critical Thinking** Regardless of the energy of the electrons used to produce ions, J. J. Thomson never could remove more than one electron from a hydrogen atom. What could he have concluded about the positive charge of a hydrogen atom?

Physics Online physicspp.com/self_check_quiz

26.2 Electric and Magnetic Fields in Space

Although you probably do not realize it, you rely on electromagnetic waves every day. Signals broadcast from television and radio stations, orbiting satellites, and even those emanating from distant galaxies are all electromagnetic waves. Electromagnetic waves also are used in common consumer products, such as microwaves ovens, remote-control garage door openers, and cellular phones, to name a few. In this section, you will learn about the fields that make up electromagnetic waves, and how the waves are produced and received.

▶ **Objectives**

- **Describe** how electromagnetic waves propagate through space.
- **Solve** problems involving electromagnetic wave properties.
- **Describe** the factors affecting an antenna's ability to receive an electromagnetic wave of a specific wavelength.
- **Solve** problems involving electromagnetic wave propagation through dielectrics.

▶ **Vocabulary**

electromagnetic wave
dielectrics
antenna
electromagnetic spectrum
electromagnetic radiation
piezoelectricity
receiver

Electromagnetic Waves

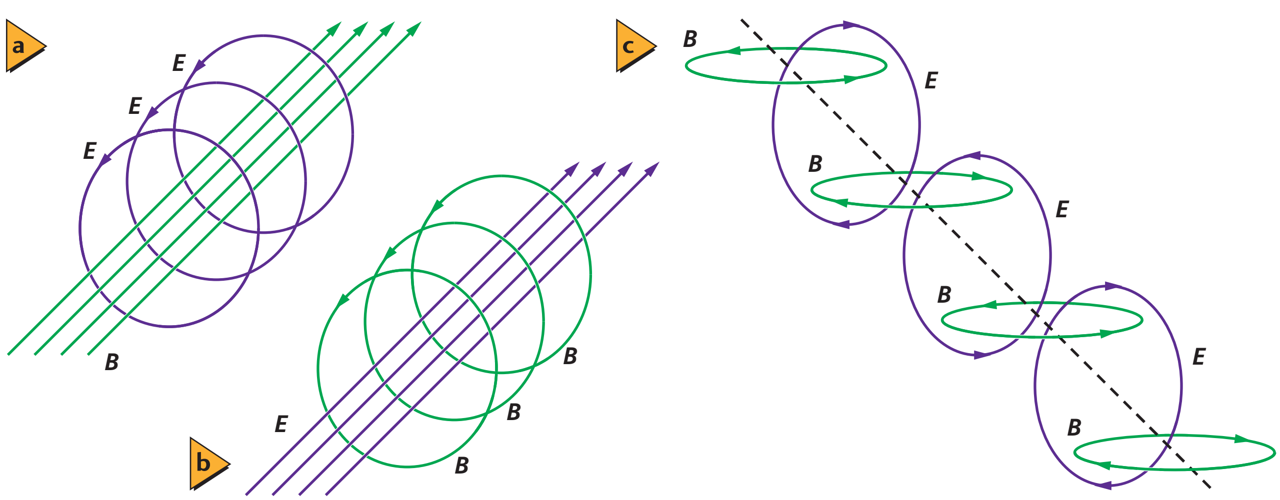
Great advancements in the understanding of electromagnetic waves were made during the nineteenth century. These advancements led to the development of new devices and technologies that had a huge impact on modern society.

A series of breakthroughs In 1821, while performing a demonstration for his students, Danish physicist Hans Christian Oersted noticed that an electric current caused the needle in a nearby compass to deflect. Oersted realized that his observation displayed a fundamental connection between electricity and magnetism. He concluded that an electric current in a conductor produces a magnetic field, and that a changing electric current produces a changing magnetic field. Oersted's discovery created excitement in the scientific community and led to a flood of new research.

Eleven years after Oersted, Englishman Michael Faraday, and American high school physics teacher Joseph Henry independently discovered induction. Induction is the production of an electric field due to a moving magnetic field. Interestingly, induced electric fields exist even if there is not a wire present, as shown in **Figure 26-5a.** Thus, a changing magnetic field produces a corresponding changing electric field. Notice that the field lines of the induced electric field, shown in Figure 26-5a, are closed loops. This is because, unlike an electrostatic field, there are no charges on which the field lines begin or end.

CLICK HERE CLICK HERE

■ **Figure 26-5** These diagrams represent an induced electric field **(a),** a magnetic field **(b),** and both electric and magnetic fields **(c).**



In 1860, Scottish physicist James Maxwell postulated that the opposite of induction is also true; that is, that a changing electric field produces a changing magnetic field. This is shown in **Figure 26-5b** on the previous page. Maxwell also suggested that charges were not necessary—a changing electric field alone would produce the magnetic field. He then predicted that both accelerating charges and changing magnetic fields would produce electric and magnetic fields that move through space.

A combined electric and magnetic field that travels through space is an **electromagnetic wave,** or EM wave. The orientations of the fields making up an electromagnetic wave are shown in **Figure 26-5c** on the previous page. In 1887, Heinrich Hertz, a German physicist, experimentally confirmed that Maxwell's theory was correct. Maxwell's theory led to a complete description of electricity and magnetism.

Electromagnetic wave properties The speed of an electromagnetic wave later was found to be approximately 3.00×10^8 m/s, now denoted as c, the speed of light. Light, a type of electromagnetic wave, and all other forms of electromagnetic waves, travel through space at c. The wavelength of an electromagnetic wave, its frequency, and the speed of light all are related.

Wavelength-Frequency Relationship for a Wave $\lambda = \frac{v}{f}$

The wavelength of a wave is equal to its speed divided by its frequency.

In this equation, the wavelength, λ, is measured in m; the speed, v, is measured in m/s; and the frequency, f, is measured in Hz. Note that for an electromagnetic wave traveling in air or a vacuum, the speed, v, is equal to c, the speed of light. Thus, for an electromagnetic wave, the equation becomes the following:

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

In the equation, $c = 3.00\times10^8$ m/s.

Note that in the wavelength-frequency equation, the product of frequency and wavelength is constant—equal to c—for any electromagnetic wave. Thus, as wavelength increases, frequency decreases, and vice-versa. In other words, an electromagnetic wave with a long wavelength has a low frequency, whereas an electromagnetic wave with a short wavelength has a high frequency.

PRACTICE Problems

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

15. What is the speed in air of an electromagnetic wave having a frequency of 3.2×10^{19} Hz?

16. What is the wavelength of green light having a frequency of 5.70×10^{14} Hz?

17. An electromagnetic wave has a frequency of 8.2×10^{14} Hz. What is the wavelength of the wave?

18. What is the frequency of an electromagnetic wave having a wavelength of 2.2×10^{-2} m?

Electromagnetic wave propagation through matter Electromagnetic waves also can travel through matter. Sunlight shining through a glass of water is an example of light waves traveling through three different forms of matter: air, glass, and water. Air, glass, and water are nonconducting materials known as **dielectrics.** The velocity of an electromagnetic wave through a dielectric is always less than the speed of the wave in a vacuum, and it can be calculated using the following equation:

$$v = \frac{c}{\sqrt{K}}$$

In this equation, the wave velocity, v, is measured in m/s; the speed of light, c, has a value of 3.00×10^8 m/s; and the relative dielectric constant, K, is a dimensionless quantity. In a vacuum, $K = 1.00000$, and the wave velocity is equal to c. In air, $K = 1.00054$, and electromagnetic waves move just slightly slower than c.

PRACTICE Problems

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

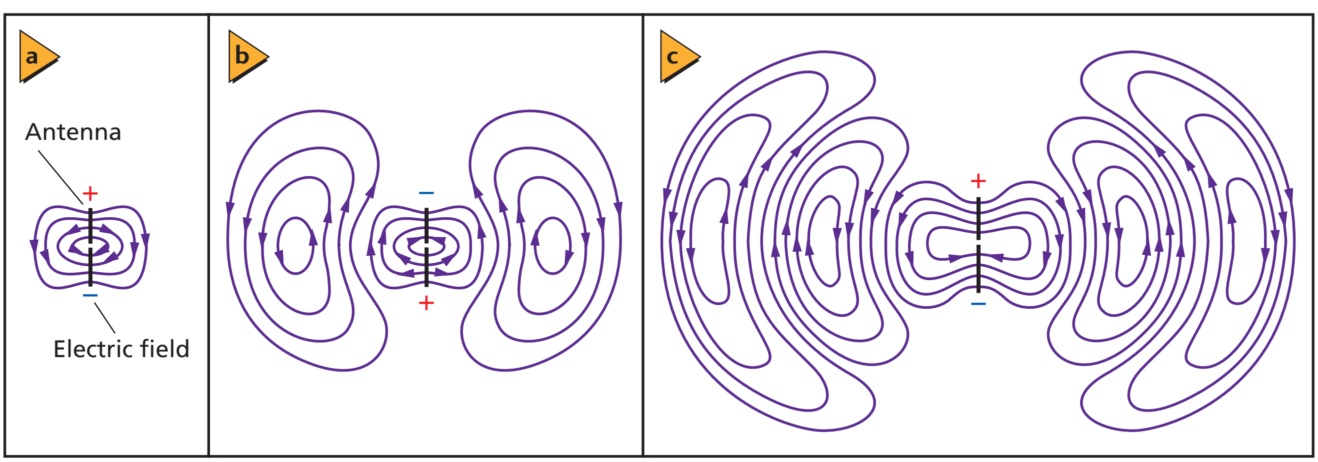
19. What is the speed of an electromagnetic wave traveling through the air? Use $c = 299{,}792{,}458$ m/s in your calculation.

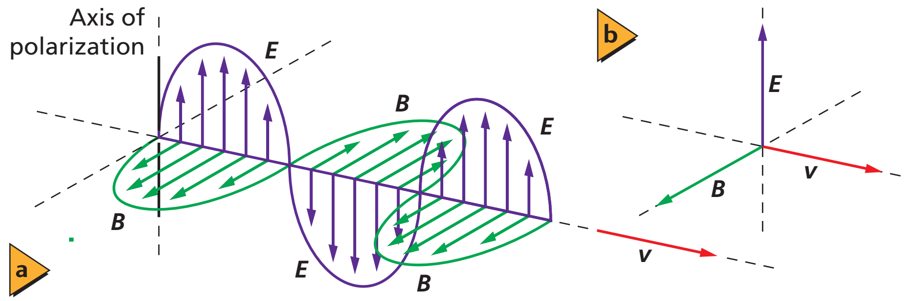
20. For light traveling through water, the dielectric constant is 1.77. What is the speed of light traveling through water?

21. The speed of light traveling through a material is 2.43×10^8 m/s. What is the dielectric constant of the material?

Electromagnetic wave propagation through space The formation of an electromagnetic wave is shown in **Figure 26-6.** An **antenna,** which is a wire designed to transmit or receive electromagnetic waves, is connected to an alternating current (AC) source. The AC source produces a varying potential difference in the antenna that alternates at the frequency of the AC source. This varying potential difference generates a corresponding varying electric field that propagates away from the antenna. The changing electric field also generates a varying magnetic field perpendicular to the page. Although the magnetic field is not shown in Figure 26-6, it also propagates away from the antenna. The combined electric and magnetic fields are electromagnetic waves that spread out into space, moving at the speed of light.

Figure 26-6 An alternating current source connected to the antenna produces a varying potential difference in the antenna. This varying potential difference generates a varying electric field **(a).** The varying electric field produces a changing magnetic field (not shown), and this magnetic field, in turn, generates an electric field. This process continues and the electromagnetic wave propagates away from the antenna, **(b)** and **(c).**

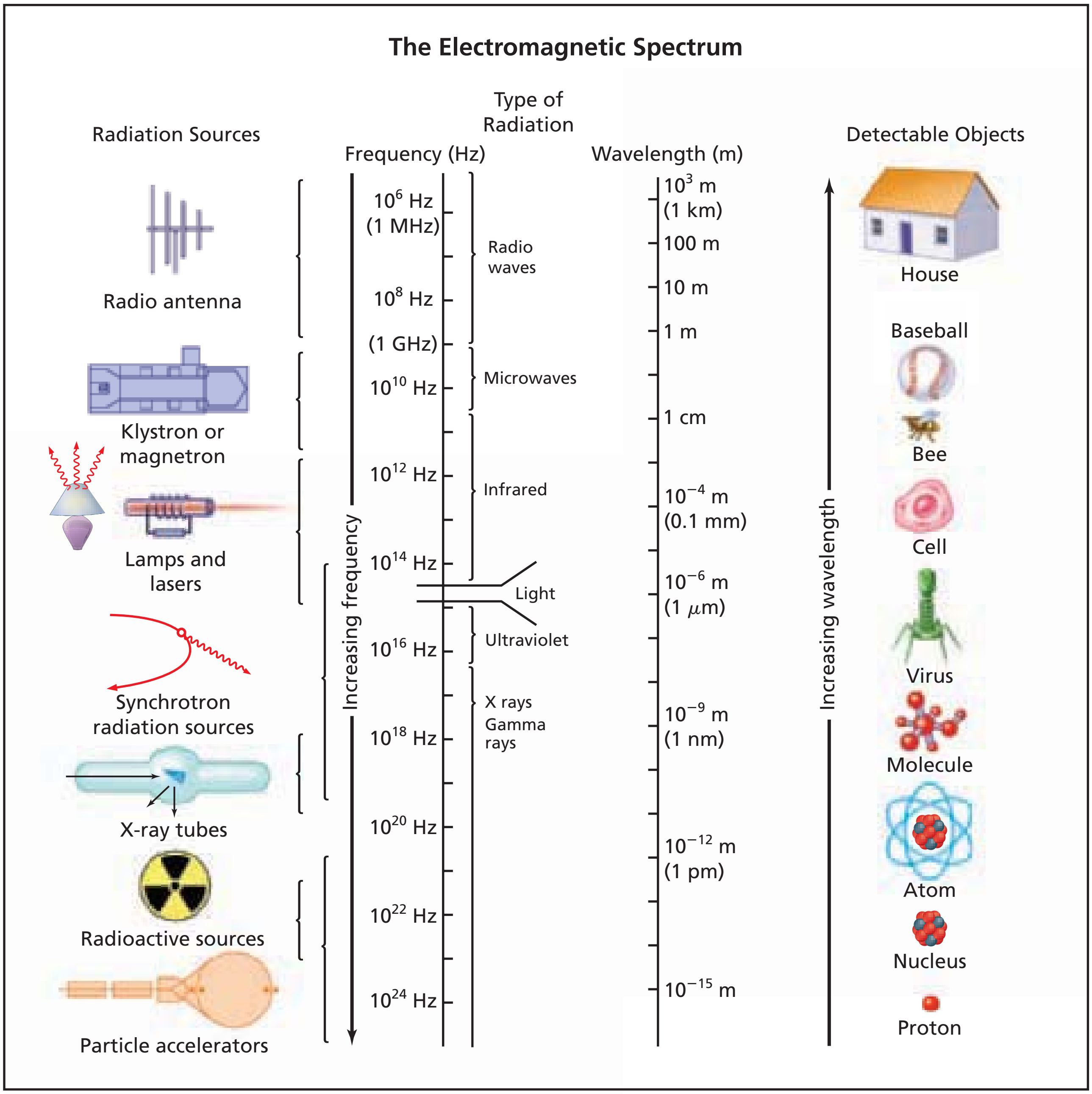




■ **Figure 26-7** Portions of the electric and magnetic fields generated by an antenna might look like this at an instant in time **(a).** Note how the electric and magnetic fields are perpendicular to each other and to the direction of the wave velocity, ***v*** **(b).**

■ **Figure 26-8** The illustration below provides examples of various types of electromagnetic radiation and their wavelengths.

If it were possible to see invisible electromagnetic waves approaching, the changing fields would appear as in **Figure 26-7.** The electric field oscillates up and down, while the magnetic field oscillates at right angles to the electric field. Both of the fields are at right angles to the wave direction. Note that an electromagnetic wave produced by an antenna is polarized; that is, its electric field is parallel to the antenna's conductor.



CHALLENGE PROBLEM

Visible light makes up only a very small portion of the entire electromagnetic spectrum. The wavelengths for some of the colors of visible light are shown in **Table 26-1.**

1. Which color of light has the longest wavelength?
2. Which color travels the fastest in a vacuum?
3. Waves with longer wavelengths diffract around objects in their path more than waves with shorter wavelengths. Which color will diffract the most? The least?
4. Calculate the frequency range for each color of light given in Table 26-1.

Table 26-1

Wavelengths of Visible Light

Color	Wavelength (nm)
Violet–Indigo	390 to 455
Blue	455 to 492
Green	492 to 577
Yellow	577 to 597
Orange	597 to 622
Red	622 to 700

Producing Electromagnetic Waves

Waves from an AC source As you just learned, an AC source connected to an antenna can transmit electromagnetic waves. The wave frequency is equal to the frequency of the rotating AC generator and is limited to about 1 kHz. The range of frequencies and wavelengths that make up all forms of electromagnetic radiation is shown in **Figure 26-8** and is called the **electromagnetic spectrum.**

Waves from a coil and a capacitor A common method of generating high-frequency electromagnetic waves is to use a coil and a capacitor connected in a series circuit. If the capacitor is charged by a battery, the potential difference across the capacitor creates an electric field. When the battery is removed, the capacitor discharges as the stored electrons flow through the coil, creating a magnetic field. When the capacitor is discharged, the coil's magnetic field collapses. A back-*EMF* then develops and recharges the capacitor in the opposite direction, and the process is repeated. When an antenna is connected across the capacitor, the fields of the capacitor are transmitted into space. One complete oscillation cycle is shown in **Figure 26-9.**

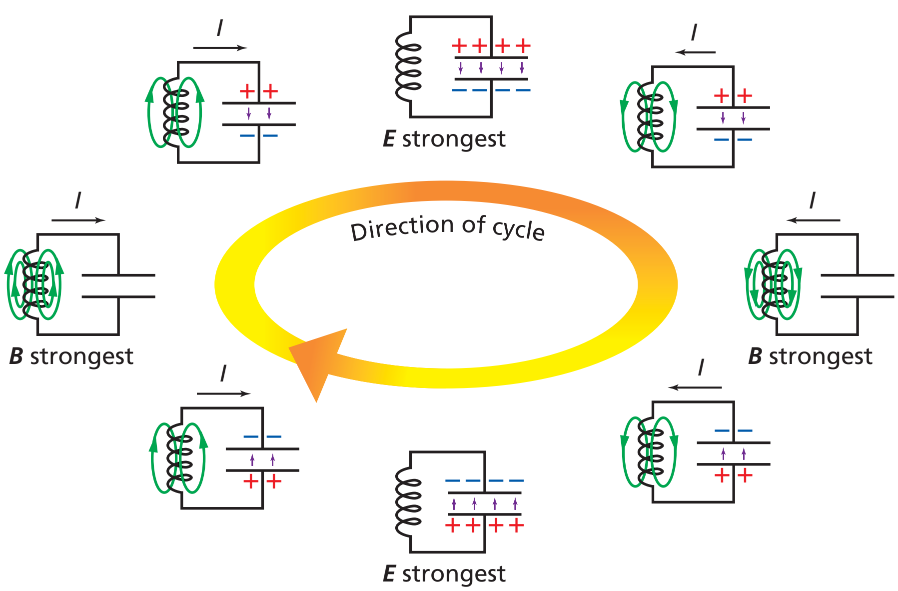


Figure 26-9 One complete oscillation cycle for a coil and capacitor circuit is shown. The capacitor and coil sizes determine the oscillations per second of the circuit, which equals the frequency of the waves produced.

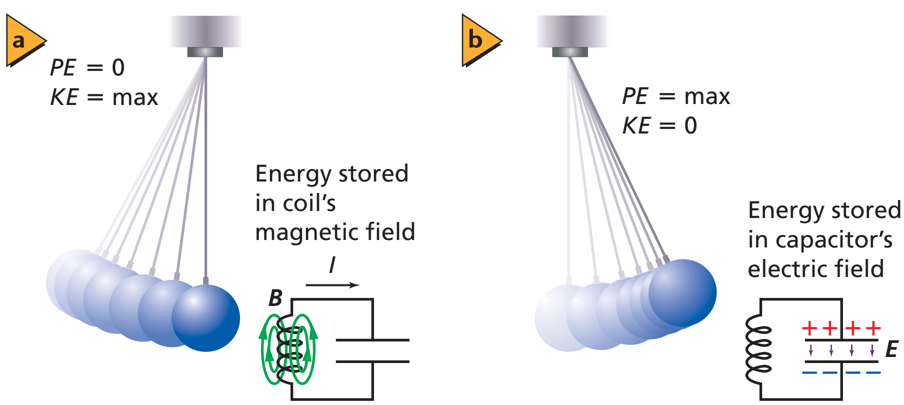
APPLYING PHYSICS

▶ **Frequencies** The Federal Communications Commission (FCC) assigns each radio and TV station a carrier wave with a specific frequency. A station broadcasts by varying its carrier wave. When the wave is received by your radio or TV set, the carrier wave is stripped away and the information from the wave is processed so that you can see or hear it. ◀

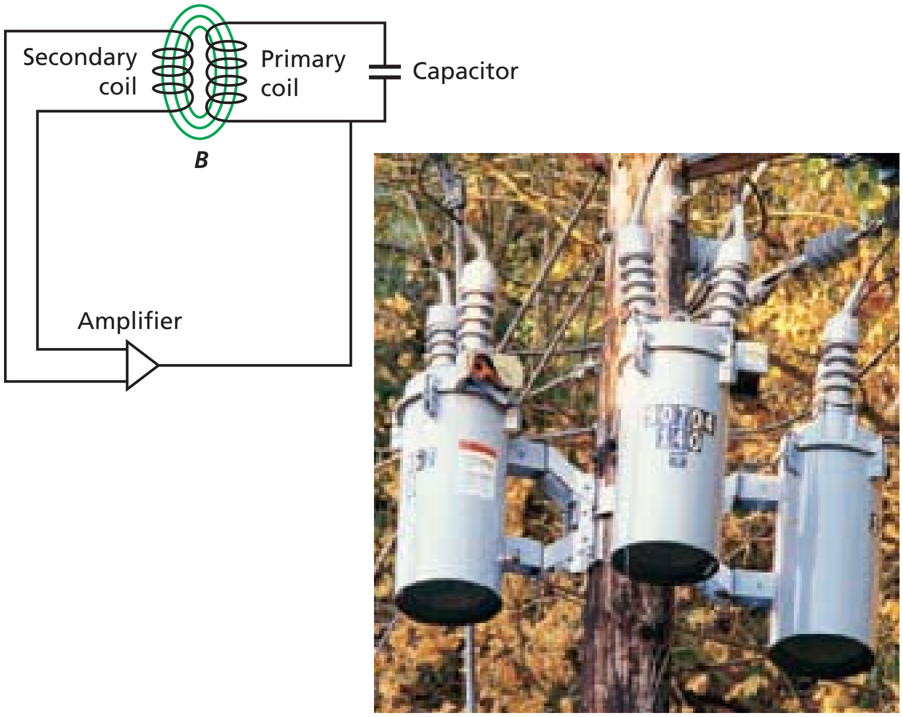
The process occurring in the coil-and-capacitor circuit can be compared with the cyclic oscillations of a swinging pendulum, as shown in **Figure 26-10.** Assume that the electrons in the coil and capacitor are represented by the pendulum's bob. The moving bob has the greatest speed at the bottom of its swing, a position at which kinetic energy, *KE*, is maximized, and potential energy, *PE*, due to gravity is zero. This point in the pendulum's motion, shown in **Figure 26-10a,** is similar to the peak electric current flow in the coil when the charge on the capacitor is zero. When the bob reaches the peak of its swing, its vertical displacement and *PE* are maximized, whereas its *KE* is zero because the bob's velocity is zero. As shown in **Figure 26-10b,** this point in the motion is similar to when the capacitor holds the maximum charge and the current through the coil is zero.

Energy in the coil-and-capacitor circuit As you just learned, the *PE* of the pendulum is largest when its vertical displacement is greatest, and the *KE* is largest when the velocity is greatest. The sum of the *PE* and *KE*—the total energy—is constant throughout the motion of the pendulum. In the coil-and-capacitor circuit, both the magnetic field produced by the coil and the electric field in the capacitor contain energy. When the current is largest, the energy stored in the magnetic field is greatest. When the current is zero, the electric field of the capacitor is largest, and all the energy is contained in the electric field. The total energy of the circuit (the sum of the magnetic field energy, the electric field energy, the thermal losses, and the energy carried away by the generated electromagnetic waves) is constant. Energy that is carried, or radiated, in the form of electromagnetic waves is frequently called **electromagnetic radiation.**

Just as a pendulum eventually stops swinging if it is left alone, the oscillations in a coil and capacitor die out over time due to resistance in the circuit. The oscillations of both systems can be made to continue by adding energy. Gentle pushes, applied at the correct times, will keep a pendulum swinging. The largest amplitude swings occur when the frequency of pushes matches the frequency of swinging motion. This is the condition of resonance, which was discussed in Chapter 14. Similarly, voltage pulses applied to the coil-and-capacitor circuit at the right frequency keep the oscillations in the circuit going. One way of doing this is to add a second coil to the circuit, to form a transformer. A transformer is shown in **Figure 26-11.** The alternating current induced in the secondary coil is increased by an amplifier and added back to the coil and capacitor. This type of circuit can produce frequencies up to approximately 400 MHz.



■ **Figure 26-10** The motion of a pendulum is analogous to the action of electrons in a coil-and-capacitor circuit. Motion of the pendulum's bob is analogous to the current flow in the circuit **(a).** The point where the pendulum's motion comes to a stop is analogous to zero current in the circuit **(b).**

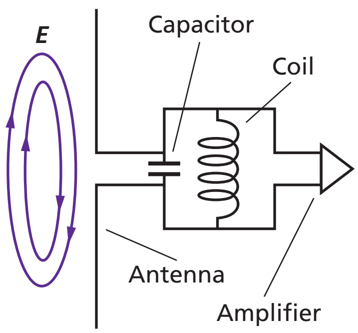


■ **Figure 26-11** In a transformer, the amplified oscillation from the secondary coil is in resonance with the coil-and-capacitor circuit and keeps the oscillations going.

Waves from a resonant cavity The oscillation frequency produced by a coil-and-capacitor circuit can be increased by decreasing the size of the coil and capacitor used. However, above frequencies of 1 GHz, individual coils and capacitors can no longer be used. High frequency microwaves, with frequencies from 1 GHz to 100 GHz, are produced using a resonant cavity. The resonant cavity is a rectangular box that acts as both a coil and a capacitor. The size of the box determines the frequency of oscillation. Microwave ovens have resonant cavities that produce the microwaves used to cook food.

To produce even higher frequency infrared waves, the size of the resonant cavity would have to be reduced to molecular size. The oscillating electrons that produce infrared waves are, in fact, within the molecules. Visible and ultraviolet waves are generated by electrons within atoms. X rays and gamma rays are the result of accelerating charges in the nuclei of atoms. All electromagnetic waves arise from accelerated charges, and all travel at the speed of light.

Waves from piezoelectricity Coils and capacitors are not the only method of generating oscillation voltages. Quartz crystals deform when a voltage is applied across them, a property known as **piezoelectricity**. The application of an AC voltage to a cut section of quartz crystal results in sustained oscillations. An inverse linear relationship exists between crystal thickness and oscillation frequency. Just as a piece of metal vibrates at a specific frequency when it is bent and released, so does a quartz crystal. A crystal can be cut so that it vibrates at a specific desired frequency. An applied voltage deforms the crystal and starts the vibrations. The piezoelectric property also generates an *EMF* when the crystal is deformed. Because this *EMF* is produced at the vibrating frequency of the crystal, it can be amplified and returned to the crystal to keep it vibrating. Because of their nearly constant frequencies of vibration, quartz crystals commonly are used in watches.



■ **Figure 26-12** The changing electric fields from a radio station signal cause electrons in the antenna to accelerate. The information carried by the signal is then decoded and amplified and used to drive a loudspeaker.

Reception of Electromagnetic Waves

Now that you know how electromagnetic waves are produced and transmitted, how do you suppose the waves are detected? As you may have guessed, reception involves an antenna. As shown in **Figure 26-12,** the wave's electric fields accelerate the electrons of the material making up the antenna. The acceleration is largest when the antenna is positioned in the same direction as the wave polarization; that is, when it is parallel to the direction of the wave's electric fields. A potential difference across the terminals of the antenna oscillates at the frequency of the electromagnetic wave. This voltage is largest when the length of the antenna is one-half the wavelength of the wave it is to detect. Thus, an antenna's length is designed to be one-half of the wavelength of the wave it is supposed to receive. For this reason, an antenna designed to receive radio and television waves is much longer than one designed to receive microwaves.

While a simple wire antenna can detect electromagnetic waves, several wires are more effective. A television antenna often consists of two or more wires spaced about one-quarter wavelength apart. Electric fields that are generated in the individual wires form constructive interference patterns that increase the strength of the signal.

It is important to realize that all electromagnetic waves, not just visible light waves, undergo reflection, refraction, and diffraction. Thus, it should not be a surprise to learn that dish antennas, like the one shown at the beginning of this chapter, reflect very short wavelength electromagnetic signals, just as parabolic mirrors reflect visible light waves. A dish antenna's large surface area for collecting and focusing waves makes it well-suited to receive weak radio signals. A parabolic dish antenna works by reflecting and focusing the received signals off its surface and into a device called the horn. The horn, which is supported by a tripod structure over the main dish, contains a short dipole antenna. The horn channels the signals to a **receiver,** a device consisting of an antenna, a coil-and-capacitor circuit, a detector to decode the signal, and an amplifier.

Selection of waves As you know, many different radio and television stations transmit electromagnetic waves at the same time. If the information being broadcast is to be understood, the waves of a particular station must be selected. To select waves of a particular frequency (and reject the others) a tuner uses a coil-and-capacitor circuit connected to an antenna. The capacitance is adjusted until the oscillation frequency of the circuit equals the frequency of the desired wave. When this is done, only waves of the desired frequency can cause significant oscillations of the electrons in the circuit.

Energy from waves Waves carry energy as well as information. At microwave and infrared frequencies, waves accelerate electrons in molecules. The energy of the waves is converted to thermal energy in the molecules. This is how microwave ovens cook food.

Biology Connection

Light waves also can transfer energy to electrons. Photographic film makes use of this fact by using the energy in light waves to drive a chemical reaction within the film. The result is a permanent record of the light from the subject that strikes the film. At higher frequencies, ultraviolet (UV) radiation causes many chemical reactions to occur, including those in living cells that produce sunburn and tanning.

X Rays

In 1895, German physicist Wilhelm Roentgen sent electrons through an evacuated glass tube, similar to the one shown in **Figure 26-13.** Roentgen used a very high voltage across the tube to give the electrons large kinetic energies. When the electrons struck the metal anode target within the tube, Roentgen noticed a glow on a phosphorescent screen a short distance away. The glow continued even when a piece of wood was placed between the tube and the screen. He concluded that some kind of highly penetrating rays were coming from the tube.

Because Roentgen did not know what these strange rays were, he called them X rays. A few weeks later, Roentgen found that photographic plates were darkened by X rays. He also discovered that soft body tissue was transparent to the rays, but that bone blocked them. He produced an X-ray picture of his wife's hand. Within months, doctors recognized the valuable medical uses of this phenomenon.

It now is known that an X ray is a high-frequency electromagnetic wave. In an X-ray tube, electrons first are accelerated to high speeds by means of potential differences of 20,000 V or more. When the electrons crash into matter, their kinetic energies are converted into the very high-frequency electromagnetic waves called X rays.

Electrons are accelerated to these speeds in cathode-ray tubes, such as the picture tube in a television. When the electrons hit the inside surface of a television screen's face plate, they come to a sudden stop and cause the colored phosphors to glow. This sudden stopping of the electrons also can produce harmful X rays. Thus, the face-plate glass in a television screen contains lead to stop the X rays and protect the viewers.

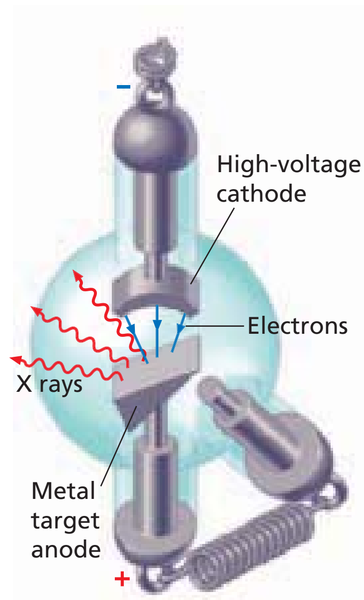


Figure 26-13 X rays are emitted when high energy electrons strike the metal target inside the X-ray tube. The target can be changed to produce X rays of different wavelengths.

26.2 Section Review

22. Wave Propagation Explain how electromagnetic waves are able to propagate through space.

23. Electromagnetic Waves What are some of the primary characteristics of electromagnetic waves? Do electromagnetic waves behave differently from the way that other waves, such as sound waves, behave? Explain.

24. Frequency An electromagnetic wave is found to have a wavelength of 1.5×10^{-5} m. What is the frequency of the wave?

25. TV Signals Television antennas normally have metal rod elements that are oriented horizontally. From this information, what can you deduce about the directions of the electric fields in television signals?

26. Parabolic Receivers Why is it important for a parabolic dish's receiving antenna to be properly aligned with the transmitter?

27. Antenna Design Television channels 2 through 6 have frequencies just below the FM radio band, while channels 7 through 13 have much higher frequencies. Which signals would require a longer antenna: those of channel 7 or those of channel 6? Provide a reason for your answer.

28. Dielectric Constant The speed of light traveling through an unknown material is 1.98×10^{8} m/s. Given that the speed of light in a vacuum is 3.00×10^{8} m/s, what is the dielectric constant of the unknown material?

29. Critical Thinking Most of the UV radiation from the Sun is blocked by the ozone layer in Earth's atmosphere. In recent years, scientists have discovered that the ozone layer over both Antarctica and the Arctic Ocean is thinning. Use what you have learned about electromagnetic waves and energy to explain why some scientists are very concerned about the thinning ozone layer.

Physics Online physicspp.com/self_check_quiz

PHYSICS LAB

Electromagnetic Wave Shielding

Alternate CBL instructions can be found on the Web site.
physicspp.com

The electromagnetic spectrum consists of many types of electromagnetic radiation, each of which can be classified by its frequency or wavelength. Gamma rays have the highest frequency and energy, and have wavelengths that are a fraction of a nanometer. Following gamma rays in order of increasing wavelength (decreasing frequency and energy) are the following forms of electromagnetic radiation: X rays, ultraviolet, visible, infrared, microwaves, and radio waves. Only wavelengths that fall within the range of visible light can be detected by the human eye—all other forms of radiation are invisible.

Electromagnetic receivers, such as those used in radios and televisions, detect waves with an antenna. Because every electrical device with a changing or alternating current radiates electromagnetic waves, waves from these sources can interfere with the reception of a desired signal. Some materials are effective at blocking or shielding radio waves. In this lab you will investigate the radio wave shielding effectiveness of various materials.

QUESTION

What types of materials shield electromagnetic waves?

Objectives

- **Experiment** with various materials to determine if they are effective at shielding electromagnetic waves.
- **Observe and infer** about types of materials that shield radio waves.
- **Collect and organize** data on types of shielding.

Safety Precautions

- **Always wear safety goggles and a lab apron.**
- **Wear gloves when bending or handling the wire screen.**
- **Use caution when working with staples to avoid puncturing skin.**

Materials

small battery-operated AM/FM radio
two small cardboard boxes
metal box or can with lid
aluminum foil
static shielding bag (type used to protect computer parts)
metal screen
masking tape
leather gloves
stapler

Procedure

1. Prepare the aluminum covered box. Cover the outside of one box and its lid with aluminum foil. Cover the lid separately from the rest of the box so the lid can be removed and replaced.
2. Prepare the wire screen box. Fold a piece of wire screen so that it forms a four-sided box shape with open ends. Use staples to hold connecting edges of the screen together. Make sure the wire box is big enough for the radio to fit inside. Next, cut a piece of wire screen to fit over each open end. Staple one of these pieces in place over one of the ends, making sure to leave no openings. Then, staple one edge of the remaining piece of wire screen to the other end of the wire box. This piece of screen will act as a door that can be opened and closed.

Horizons Companies

Data Table

Band	Frequency (Hz)	Enclosure	Observations	Band	Frequency (Hz)	Enclosure	Observations
AM		A person's arms		FM		A person's arms	
AM		Cardboard box		FM		Cardboard box	
AM		Cardboard box covered with aluminum foil		FM		Cardboard box covered with aluminum foil	
AM		Wire screen box		FM		Wire screen box	
AM		Metal box		FM		Metal box	
AM		Static shielding bag		FM		Static shielding bag	

3. Turn on the radio and tune it to a strong signal from a station in the AM band. Record the frequency of the station. The frequency can be determined from the radio dial or display, or the station's broadcast frequency may be announced while you are listening.
4. Hold the radio next to your body and cover it with your arms. Ignoring the fact than the sound is muffled because you are covering the speaker, how has the reception of the signal been affected? Record your observations.
5. Place the radio inside a cardboard box and put the lid on the box. Listen to the radio's reception and record your observations.
6. Repeat step 5 four more times using the aluminum foil covered box, the wire screen box (with the door closed), the metal box (with lid on), and the static shielding bag, respectively.
7. Change the radio to the FM band and tune in a strong station. Record the frequency of the station and then repeat steps 4–6.

Analyze

1. **Summarize** Which materials were effective at shielding radio waves?
2. **Use Numbers** Calculate the wavelengths for each of the radio frequencies you used. Recall that $c = f\lambda$, where the velocity, c, of the electromagnetic waves is 3.00×10^8 m/s.
3. **Compare and Contrast** How does the wavelength of the tuned-in radio signal compare to the size of holes or openings in the materials used to shield the radio?
4. **Interpret Data** What did the materials that effectively shielded the radio from receiving signals have in common?

Conclude and Apply

1. **Explain** Offer an explanation of what might be happening to the electric and magnetic fields of the radio wave fields that are blocked from reaching the radio by the shielding materials.
2. **Infer** Why was covering the radio with your arms not effective at blocking the radio waves?
3. **Use Scientific Explanations** Ocean water absorbs radio waves, limiting their penetration below the surface to a depth equal to approximately one wavelength. Because of this, very low frequency (40–80 Hz) radio waves are used to contact submerged submarines. Why might the site for a high-powered radio transmitter used for submarine communication be located in a remote area far from the ocean? *(Hint: Estimate the length if a one-half wavelength antenna were used.)*

Going Further

How does the size of the small holes in the metal screen of a microwave oven door compare to the wavelength of a 2.4-GHz microwave?

Real-World Physics

Suppose you want to mail some photos or an audio recording stored on a magnetic computer diskette to a friend. What should you do to protect the diskette from electromagnetic waves during shipping?

Physics Online

To find out more about electromagnetic waves, visit the Web site: **physicspp.com**

Technology and Society

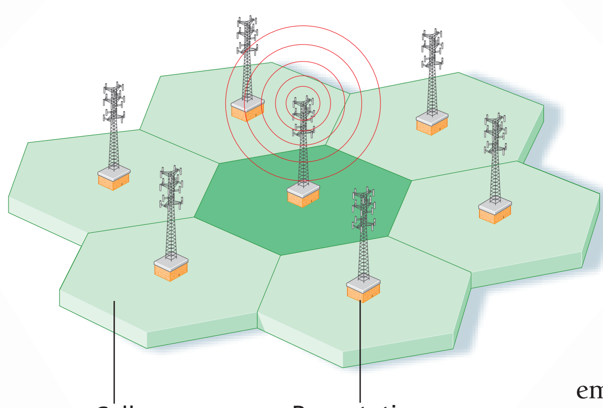
Cellular Phones

Do you own a cellular phone? Once rare and expensive, cell phones are now commonplace and relatively affordable. Approximately 60 percent of American teenagers have one.

Cellular Networks The cell phone gets its name from the way cell-phone companies divide a city into small regions called *cells.* Each cell is a hexagon-shaped zone within a larger hexagonal grid. Cells are typically about 26 square kilometers in area, though they vary in size depending on terrain and the number of cell phone users. Located within each cell is a base station, consisting of a tall tower-like structure and boxes or buildings that contain radio equipment. When you make a call, the signal from your phone is transmitted to the base station located within your cell. This signal then is transmitted from the local base station to the base station where the person you are calling is located.

How then, do cell phones communicate with base stations? Cell phones use radio waves to transmit information to and receive information from base stations. A cell phone is essentially a two-way radio containing both a radio transmitter and a radio receiver. The cell-phone transmitter takes the sound of your voice, encodes it onto a radio-frequency wave and then transmits the radio wave to a nearby base station. The base station then relays the signal to the destination base station by broadcasting radio waves through the air. On the receiving end of the call, the cell phone picks up the radio signal, decodes it, and reconverts it into audible sounds you can understand. By making use of two different frequencies (one frequency for talking and one frequency for listening) both people connected by the call can talk at the same time.

Network of Base Stations



A cellular phone company's system of base stations can relay your call all the way across the country, even when both people involved in the call are moving. When you move from cell to cell, the signal is automatically relayed to the correct base station in the system.

Risks of Cell Phone Use Using a cell phone is not a risk-free activity. For example, driving while talking on a cell phone is dangerous. One study found that people talking on their cell phones while driving were four times more likely to be involved in an accident than non-cell phone users. Some service stations post warning signs prohibiting cell phone use. Static electricity generated by the cell phone might cause the gasoline fumes to ignite.

Another potential risk is more controversial. Because cell phones broadcast radio waves, they emit electromagnetic energy known as radio-frequency (RF) energy. There is some evidence that cell phones emit enough radiation to cause severe health problems, such as brain cancer and Alzheimer's disease. There is evidence supporting both sides of the debate. Currently, no one knows for certain what the long-term health effects of cell phone use are, if any.

Going Further

1. **Use Scientific Explanations** How did cellular phones get their name?
2. **Compare and Contrast** How are an AM/FM radio and a cellular phone similar? How are they different?
3. **Critical Thinking** Explain why the low-power transmitters used by cell phones are important in keeping the phones lightweight.

Chapter 26

Study Guide

26.1 Interactions of Electric and Magnetic Fields and Matter

Vocabulary

- isotope (p. 701)
- mass spectrometer (p. 701)

Key Concepts

- The ratio of charge to mass of an electron was measured by J. J. Thomson using balanced electric and magnetic fields in a cathode-ray tube.

$$\frac{q}{m} = \frac{v}{Br}$$

- An electron's mass can be found by combining Thomson's result with Millikan's measurement of the electron's charge.
- Atoms of the same element can have different masses.
- The mass spectrometer uses both electric and magnetic fields to measure the masses of ionized atoms and molecules.
- The mass spectrometer can be used to determine the charge-to-mass ratio of an ion.

$$\frac{q}{m} = \frac{2V}{B^2r^2}$$

26.2 Electric and Magnetic Fields in Space

Vocabulary

- electromagnetic wave (p. 706)
- dielectrics (p. 707)
- antenna (p. 707)
- electromagnetic spectrum (p. 709)
- electromagnetic radiation (p. 710)
- piezoelectricity (p. 711)
- receiver (p. 712)

Key Concepts

- Electromagnetic waves are coupled, changing electric and magnetic fields that move through space.
- The wavelength of a wave is equal to its speed divided by its frequency.

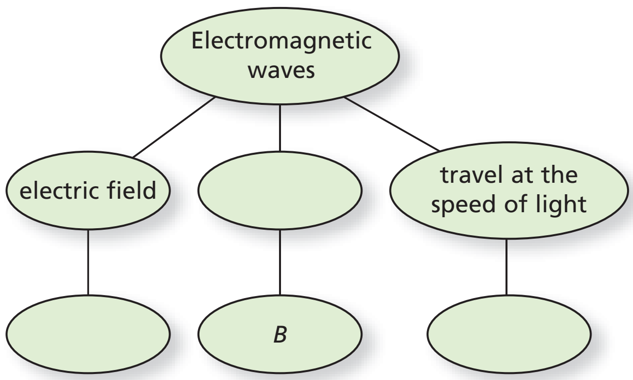
$$\lambda = \frac{v}{f}$$

  For an electromagnetic wave traveling in a vacuum, the speed in the above equation, v, is equal to the speed of light, c.
- The velocity of an electromagnetic wave through a dielectric is less than the speed of light in a vacuum.
- A changing current in a transmitting antenna is used to generate electromagnetic waves.
- Electromagnetic radiation can transmit energy and information through a medium or a vacuum.
- Piezoelectricity is the property of a crystal causing it to bend or deform and produce electrical vibrations when a voltage is applied across it.
- Receiving antennas convert electromagnetic waves to varying electric fields in conductors.
- Electromagnetic waves can be detected by the *EMF* that they produce in an antenna. Particular frequencies of electromagnetic waves can be selected by using a resonating coil-and-capacitor circuit, known as a tuner.
- A receiver obtains transmitted information from electromagnetic waves.
- The length of the most efficient antenna is one-half the wavelength of the wave to be detected.
- Microwave and infrared waves can accelerate electrons in molecules, thereby producing thermal energy.
- X rays are high-frequency electromagnetic waves emitted by rapidly accelerated electrons.

Chapter 26 Assessment

Concept Mapping

30. Complete the following concept map using the following term and symbols: *E*, *c*, *magnetic field*.



Mastering Concepts

31. What are the mass and charge of an electron? (26.1)

32. What are isotopes? (26.1)

33. The direction of an induced magnetic field is always at what angle to the changing electric field? (26.2)

34. Why must an AC generator be used to propagate electromagnetic waves? If a DC generator were used, when would it create electromagnetic waves? (26.2)

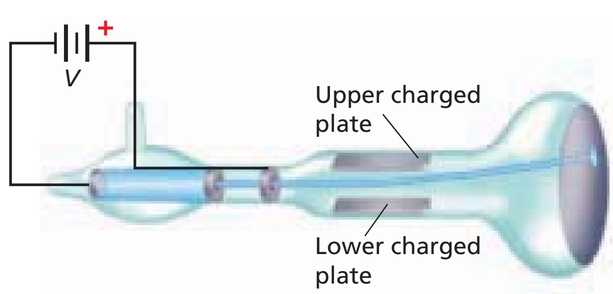
35. A vertical antenna wire transmits radio waves. Sketch the antenna and the electric and magnetic fields that it creates. (26.2)

36. What happens to a quartz crystal when a voltage is applied across it? (26.2)

37. How does an antenna's receiving circuit select electromagnetic radio waves of a certain frequency and reject all others? (26.2)

Applying Concepts

38. The electrons in a Thomson tube travel from left to right, as shown in **Figure 26-14.** Which deflection plate should be charged positively to bend the electron beam upward?

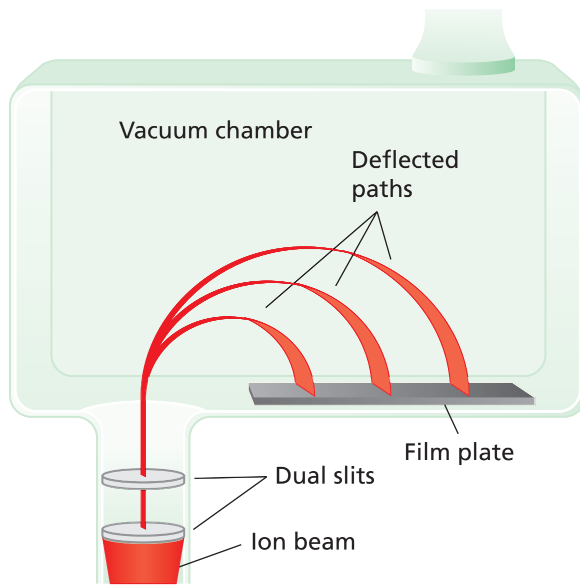


■ **Figure 26-14**

39. The Thomson tube in question 38 uses a magnetic field to deflect the electron beam. What would the direction of the magnetic field need to be to bend the beam downward?

40. Show that the units of E/B are the same as the units for velocity.

41. The vacuum chamber of a mass spectrometer is shown in **Figure 26-15.** If a sample of ionized neon is being tested in the mass spectrometer, in what direction must the magnetic field be directed to bend the ions into a clockwise semicircle?



■ **Figure 26-15**

42. If the sign of the charge on the particles in question 41 is changed from positive to negative, do the directions of either or both of the fields have to be changed to keep the particles undeflected? Explain.

43. For each of the following properties, identify whether radio waves, light waves, or X rays have the largest value.
a. wavelength
b. frequency
c. velocity

44. **TV Waves** The frequency of television waves broadcast on channel 2 is about 58 MHz. The waves broadcast on channel 7 are about 180 MHz. Which channel requires a longer antenna?

45. Suppose the eyes of an alien being are sensitive to microwaves. Would you expect such a being to have larger or smaller eyes than yours? Why?

Mastering Problems

26.1 Interactions of Electric and Magnetic Fields and Matter

46. Electrons moving at 3.6×10^4 m/s pass through an electric field with an intensity of 5.8×10^3 N/C. How large a magnetic field must the electrons also experience for their path to be undeflected?

47. A proton moves across a 0.36-T magnetic field, as shown in **Figure 26-16.** If the proton moves in a circular path with a radius of 0.20 m, what is the speed of the proton?

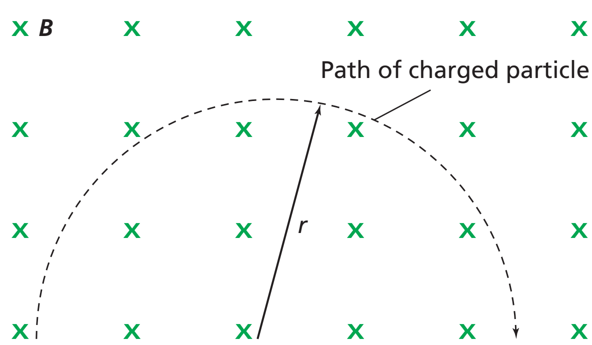


Figure 26-16

48. A proton enters a 6.0×10^{-2}-T magnetic field with a speed of 5.4×10^4 m/s. What is the radius of the circular path it follows?

49. An electron is accelerated by a 4.5-kV potential difference. How strong a magnetic field must be experienced by the electron if its path is a circle of radius 5.0 cm?

50. A mass spectrometer yields the following data for a beam of doubly ionized (2+) sodium atoms: $B = 8.0\times10^{-2}$ T, $q = 2(1.60\times10^{-19}$ C), $r = 0.077$ m, and $V = 156$ V. Calculate the mass of a sodium atom.

51. An alpha particle has a mass of approximately 6.6×10^{-27} kg and has a charge of 2+. Such a particle is observed to move through a 2.0-T magnetic field along a path of radius 0.15 m.

a. What speed does the particle have?

b. What is its kinetic energy?

c. What potential difference would be required to give it this kinetic energy?

52. A mass spectrometer analyzes carbon-containing molecules with a mass of 175×10^3 proton masses. What percent differentiation is needed to produce a sample of molecules in which only carbon isotopes of mass 12, and none of mass 13, are present?

53. Silicon Isotopes In a mass spectrometer, ionized silicon atoms have curvatures, as shown in **Figure 26-17.** If the smaller radius corresponds to a mass of 28 proton masses, what is the mass of the other silicon isotope?

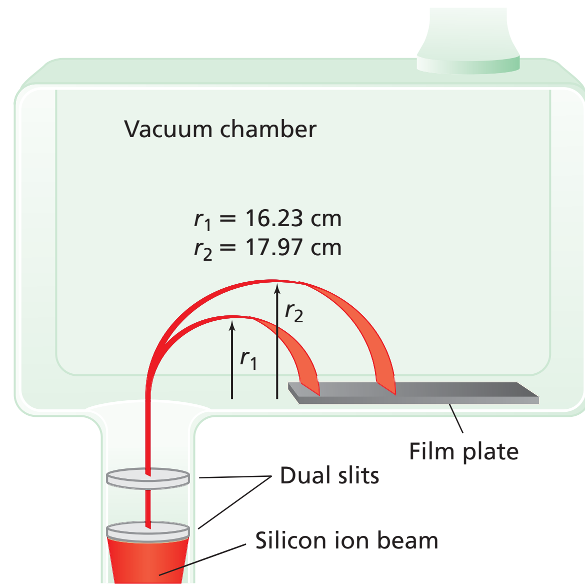


Figure 26-17

26.2 Electric and Magnetic Fields in Space

54. Radio Waves The radio waves reflected by a parabolic dish are 2.0 cm long. How long should the antenna be that detects the waves?

55. TV A television signal is transmitted on a carrier frequency of 66 MHz. If the wires on a receiving antenna are placed $\frac{1}{4}\lambda$ apart, determine the physical distance between the receiving antenna wires.

56. Bar-Code Scanner A bar-code scanner uses a laser light source with a wavelength of about 650 nm. Determine the frequency of the laser light source.

57. What is the optimum length of a receiving antenna that is to receive a 101.3-MHz radio signal?

58. An EM wave with a frequency of 100-MHz is transmitted through a coaxial cable having a dielectric constant of 2.30. What is the velocity of the wave's propagation?

59. Cell Phone A certain cellular telephone transmitter operates on a carrier frequency of 8.00×10^8 Hz. What is the optimal length of a cell phone antenna designed to receive this signal? Note that single-ended antennas, such as those used by cell phones, generate peak *EMF* when their length is one-fourth the wavelength of the wave.

Mixed Review

60. The mass of a doubly ionized (2+) oxygen atom is found to be 2.7×10^{-26} kg. If the mass of an atomic mass unit (amu) is equal to 1.67×10^{-27} kg, how many atomic mass units are in the oxygen atom?

61. Radio An FM radio station broadcasts on a frequency of 94.5 MHz. What is the antenna length that would give the best reception for this station?

62. At what frequency does a cell phone with an 8.3-cm-long antenna send and receive signals? Recall from question 59 that single-ended antennas, such as those used by cell phones, generate peak *EMF* when their length is one-fourth the wavelength of the wave they are broadcasting or receiving.

63. An unknown particle is accelerated by a potential difference of 1.50×10^{2} V. The particle then enters a magnetic field of 50.0 mT, and follows a curved path with a radius of 9.80 cm. What is the ratio of q/m?

Thinking Critically

64. Apply Concepts Many police departments use radar guns to catch speeding drivers. A radar gun is a device that uses a high-frequency electromagnetic signal to measure the speed of a moving object. The frequency of the radar gun's transmitted signal is known. This transmitted signal reflects off of the moving object and returns to the receiver on the radar gun. Because the object is moving relative to the radar gun, the frequency of the returned signal is different from that of the originally transmitted signal. This phenomenon is known as the Doppler shift. When the object is moving toward the radar gun, the frequency of the returned signal is greater than the frequency of the original signal. If the initial transmitted signal has a frequency of 10.525 GHz and the returned signal shows a Doppler shift of 1850 Hz, what is the speed of the moving object? Use the following equation:

$$v_{\text{target}} = \frac{cf_{\text{Doppler}}}{2f_{\text{transmitted}}}$$

Where,

v_{target} = velocity of target (m/s)

c = speed of light (m/s)

f_{Doppler} = Doppler shift frequency (Hz)

$f_{\text{transmitted}}$ = frequency of transmitted wave (Hz)

65. Apply Concepts H. G. Wells wrote a science-fiction novel called *The Invisible Man,* in which a man drinks a potion and becomes invisible, although he retains all of his other faculties. Explain why an invisible person would not be able to see.

66. Design an Experiment You are designing a mass spectrometer using the principles discussed in this chapter, but with an electronic detector replacing the photographic film. You want to distinguish singly ionized (1+) molecules of 175 proton masses from those with 176 proton masses, but the spacing between adjacent cells in your detector is 0.10 mm. The molecules must have been accelerated by a potential difference of at least 500.0 V to be detected. What are some of the values of V, B, and r that your apparatus should have?

Writing in Physics

67. Compose a 1–2 page report in which you outline the operation of a typical television, DVD, or VCR infrared remote-control unit. Explain why the simultaneous use of multiple remote-control units typically does not cause the units to interfere with each other. Your report should include block diagrams and sketches.

Cumulative Review

68. A He–Ne laser (λ = 633 nm) is used to illuminate a slit of unknown width, forming a pattern on a screen that is located 0.95 m behind the slit. If the first dark band is 8.5 mm from the center of the central bright band, how wide is the slit? (Chapter 19)

69. The force between two identical metal spheres with the charges shown in **Figure 26-18** is F. If the spheres are touched together and returned to their original positions, what is the new force between them? (Chapter 20)

Figure 26-18

70. What is the electric field strength between two parallel plates spaced 1.2 cm apart if a potential difference of 45 V is applied to them? (Chapter 21)

71. Calculate the daily cost of operating an air compressor that runs one-fourth of the time and draws 12.0 A from a 245-V circuit if the cost is \$0.0950 per kWh. (Chapter 22)

72. A 440-cm length of wire carrying 7.7 A is at right angles to a magnetic field. The force on the wire is 0.55 N. What is the strength of the field? (Chapter 24)

73. A north-south wire is moved toward the east through a magnetic field that is pointing down, into Earth. What is the direction of the induced current? (Chapter 25)

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

Standardized Test Practice

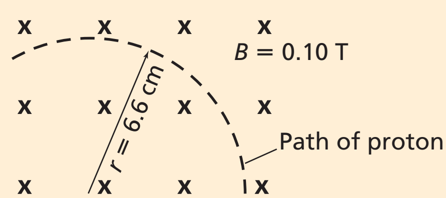
Multiple Choice

1. For a charged particle moving in a circular trajectory, ________.

- Ⓐ the magnetic force is parallel to the velocity and is directed toward the center of the circular path
- Ⓑ the magnetic force may be perpendicular to the velocity and is directed away from the center of the circular path
- Ⓒ the magnetic force always remains parallel to the velocity and is directed away from the center of the circular path
- Ⓓ the magnetic force always remains perpendicular to the velocity and is directed toward the center of the circular path

2. The radius of the circular path that a proton travels while in a constant 0.10-T magnetic field is 6.6 cm. What is the velocity of the proton?

- Ⓐ 6.3×10^{5} m/s
- Ⓑ 2.0×10^{6} m/s
- Ⓒ 6.3×10^{7} m/s
- Ⓓ 2.0×10^{12} m/s



3. The dielectric constant of ruby mica is 5.4. What is the speed of light as it passes through ruby mica?

- Ⓐ 3.2×10^{3} m/s
- Ⓑ 9.4×10^{4} m/s
- Ⓒ 5.6×10^{7} m/s
- Ⓓ 1.3×10^{8} m/s

4. A certain radio station broadcasts with waves that are 2.87 m long. What is the frequency of the radio waves?

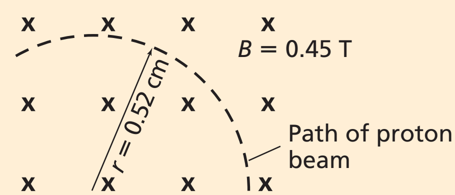
- Ⓐ 9.57×10^{-9} Hz
- Ⓑ 3.48×10^{-1} Hz
- Ⓒ 1.04×10^{8} Hz
- Ⓓ 3.00×10^{8} Hz

5. Which one of the following situations does not create an electromagnetic wave?

- Ⓐ Direct current (DC) voltage is applied to a piezoelectric quartz crystal.
- Ⓑ Current passes through a wire contained inside a plastic pipe.
- Ⓒ Current passes through a coil-and-capacitor circuit with a molecular-size resonant cavity.
- Ⓓ High energy electrons strike a metal target in an X-ray tube.

6. A proton beam has a radius of 0.52 m as it moves perpendicular to a magnetic field of 0.45 T. If the mass of an individual proton is 1.67×10^{-27} kg, what is the speed of the protons making up the beam?

- Ⓐ 1.2 m/s
- Ⓑ 4.7×10^{3} m/s
- Ⓒ 2.2×10^{7} m/s
- Ⓓ 5.8×10^{8} m/s



Extended Answer

7. A deuteron (the nucleus of deuterium) has a mass of 3.34×10^{-27} kg and a charge of $+e$. It travels in a magnetic field of 1.50 T in a circular path, with a radius of 0.0400 m. What is the velocity of the particle?

✓ Test-Taking TIP

Watch the Little Words

Underline words such as *never, always, least, not,* and *except* when you see them in test questions. These small words dramatically impact the meaning of a question.