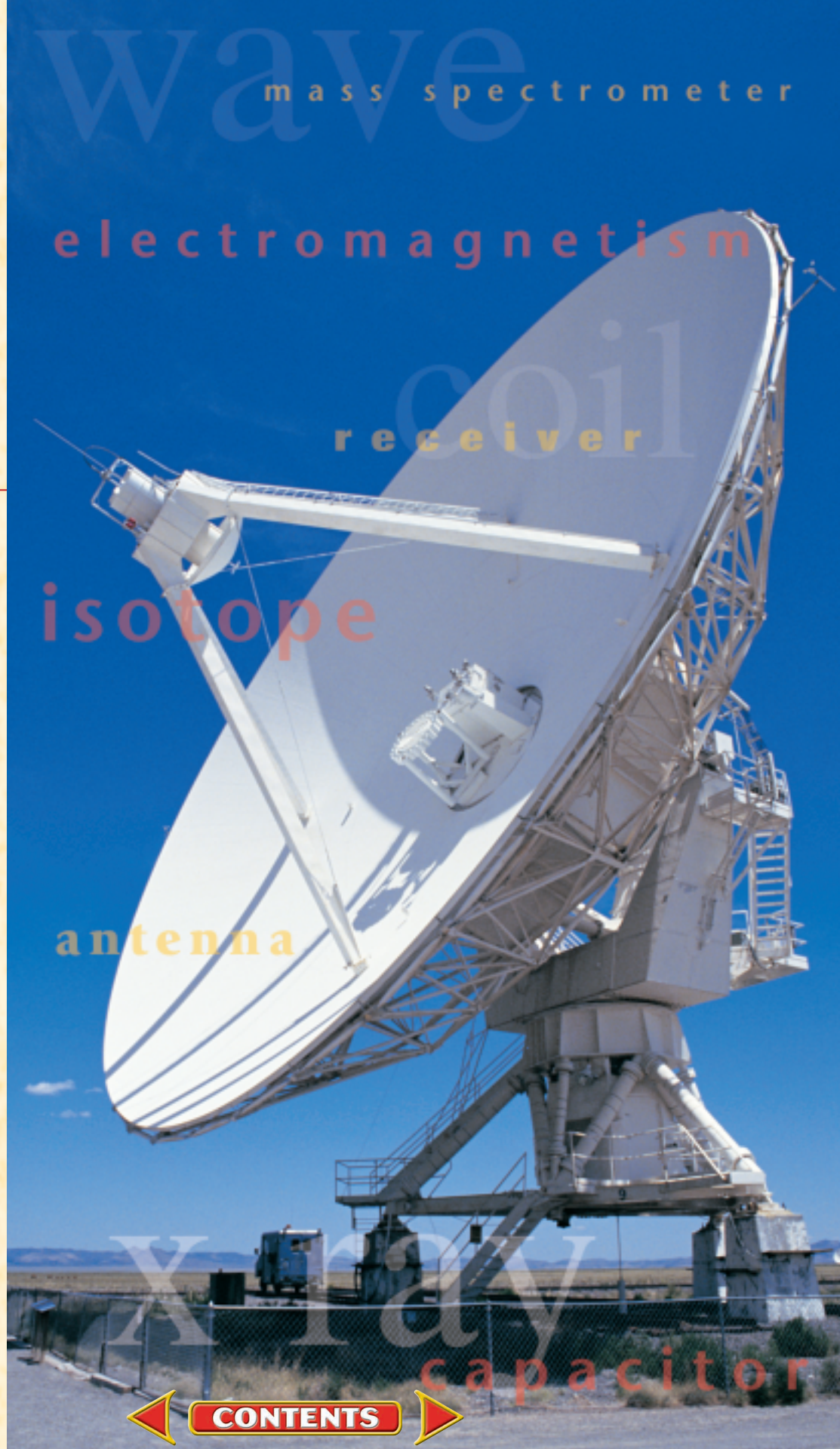


Big Ears

This parabolic dish antenna is designed to receive television signals from satellites orbiting hundreds of kilometers above Earth's surface.

Why are dish-style antennas rather than more familiar television or radio antennas used for detecting radio signals from deep space?

➡ Look at the text on page 619 for the answer.



CHAPTER

26

Electro- magnetism



Messages are everywhere around you. They fly through the air 24 hours a day, 7 days a week. For example, beeps speed from one pager to the next, and calls travel from one cell phone to another. But how? How do these messages travel from one place to the next without wires? Enter electromagnetic radiation.

Electromagnetic radiation is comprised of electromagnetic waves that are produced by an electric field and a magnetic field moving through space. Electromagnetic waves travel at the fastest speed possible—the speed of light—and they don't need material through which to move. These speedy waves efficiently carry messages.

If there are intelligent beings on another planet, either in our galaxy or in a far-off galaxy, how might they communicate with people on Earth? They, too, would probably employ electromagnetic waves to carry their messages. The universe is fairly quiet in the microwave region of the electromagnetic spectrum. Thus, microwaves seem ideal for transmitting messages over long distances.

How might we receive such messages? Huge parabolic dish antennas can detect electromagnetic waves from space. Like a parabolic mirror for visible light, the parabolic dish can focus the waves that reach it. These antennas presently receive information sent from space probes in our solar system and pick up random signals from distant galaxies. However, they could also receive messages from hypothetical extraterrestrial beings. In this chapter, you'll learn about the relationship between electric and magnetic fields and their interaction with matter.

WHAT YOU'LL LEARN

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

WHY IT'S IMPORTANT

- Mass spectrometers are widely used in many branches of science.
- Radio and TV, light and X rays—all these electromagnetic waves play vital roles in our lives.



To find out more about electromagnetism, visit the Glencoe Science Web site at science.glencoe.com



Interaction Between Electric and Magnetic Fields and Matter



OBJECTIVES

- **Describe** the measurement of the charge-to-mass ratio of the electron and **solve** problems related to this measurement.
- **Explain** how a mass spectrometer separates ions of different masses and **solve** problems involving this instrument.

F.Y.I.

Sir Joseph John Thomson was awarded the Nobel Prize in Physics in 1906 for his work on the electron. In 1908, he was knighted. Eventually, seven of his former research assistants won Nobel prizes.

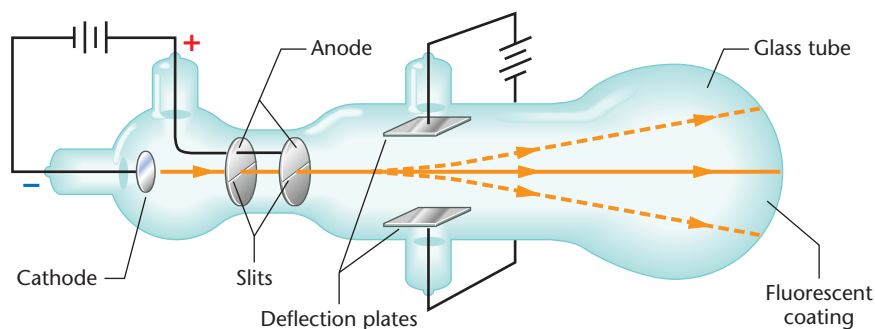
The source of most radio and television waves is accelerating electrons. It is the electrons' charge that results in electric fields, and the electrons' motion that produces magnetic fields. Electrons are also part of every atom that makes up the dish antennas that receive the waves. Therefore, it is important to understand some of the properties of electrons. The same techniques used to study electrons can be extended to study the properties of positive ions, which are atoms stripped of one or more electrons.

Mass of the Electron

The charge of an electron was first measured by Robert Millikan, using the force of an electric field on the charge on an oil drop, as described in Chapter 21. The mass of an electron, however, is far too small to measure directly on an ordinary balance. But it is possible to find the charge-to-mass ratio of an electron, q/m , by utilizing the forces of electric and magnetic fields acting on a moving electron. This can be accomplished by measuring deflections of electrons in cathode-ray tubes. From this ratio and the charge, the mass can be found.

Thomson's experiments with electrons The ratio of charge to mass of an electron was first measured in 1897 by British physicist J. J. Thomson (1856–1940). For his experiment, he used a cathode-ray tube similar to the one shown in **Figure 26–1**. In this experiment, all air is removed from the glass tube. An electric field accelerates electrons off the negatively charged cathode and toward the positively charged anode. Some of the electrons pass through a slit in the anode and travel in a narrow beam toward a fluorescent coating. When the electrons hit the coating, they cause it to glow at the point where the electrons hit.

FIGURE 26–1 The charge-to-mass ratio of an electron was first measured with the Thomson adaptation of a cathode-ray tube. In the diagram, the electromagnets have been removed to show the deflection plates. When the tube is in use, the electromagnets and the deflection plates lie in the same plane.



Electric and magnetic fields in the center of the tube exert forces on the electrons. The electric field is produced by charged parallel plates and is perpendicular to the beam. The electric field, of intensity E , produces a force, qE , on the electrons that deflects the electrons upward. The magnetic field is produced by two coils and is 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. The magnitude of the force exerted on the electrons by the magnetic field is equal to Bqv . Here, B is the magnetic field strength, and v is the electron velocity. The magnetic force depicted in **Figure 26–1** acts downward.

The electric and magnetic fields may be adjusted until the beam of electrons follows a straight, or undeflected, path. Then the forces due to the two fields are equal in magnitude and opposite in direction, and the following equation is true.

$$Bqv = Eq$$

Solving this equation for v , the following expression is obtained.

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

This equation reveals 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 a centripetal acceleration of the electrons. They follow a circular path with radius r . Using Newton's second law of motion, the following equation can be obtained.

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

Solving for q/m results in the following equation.

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

Thomson calculated the straight trajectory velocity, v , using measured values of E and B . Next, he measured the distance between the undeflected spot and the position of the spot when only the magnetic field acted on the electrons. Using this distance, he calculated the radius of the circular path of the electron, r . This allowed Thomson to calculate q/m . The average of many experimental trials produced the value $q/m = 1.759 \times 10^{11}$ C/kg. Based on the value $q = 1.602 \times 10^{-19}$ C, the mass of the electron, m , can be calculated.

$$m = \left(\frac{q}{q/m} \right) = \frac{1.602 \times 10^{-19} \text{ C}}{1.759 \times 10^{11} \text{ C/kg}} = 9.107 \times 10^{-31} \text{ kg}$$

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

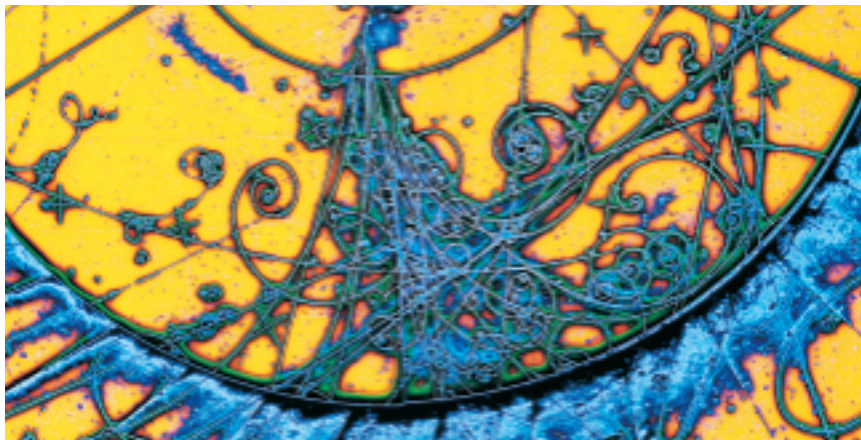
HELP WANTED

BROADCAST TECHNICIAN

An electronics and computer whiz is needed to be the technical expert of a large TV station to monitor and adjust equipment, as well as to troubleshoot and repair it in high-pressure situations. An associate degree or a vocational/technical school background, with knowledge of current FCC rules and appropriate licensure certification, is necessary. For information on careers and schools offering preparation in this field, contact:
National Association of Broadcasters
1771 N. Street, N.W.
Washington, DC 20036



FIGURE 26–2 This photograph shows the circular tracks of electrons (e^-) and positrons (e^+) moving through the magnetic field in a bubble chamber. Note that the electrons and positrons curve in opposite directions.



Thomson's experiments with protons Thomson put his apparatus to an additional use by finding q/m for positive ions in the same way that he measured the quantity for electrons. He took advantage of the fact that positively charged particles, when they are in either an electric field or a magnetic field, bend the opposite way from electrons. This is shown in **Figure 26–2**. To accelerate positively charged particles into the deflection region, he reversed the direction of the field between the cathode and anode. A small amount of hydrogen gas was then put into the tube. The field pulled the electrons off the hydrogen atoms, leaving them with a net positive charge, and accelerated these positively charged protons through a tiny slit in the negatively charged anode. The proton beam then passed through the electric and magnetic deflecting fields to the fluorescent coating of the Thomson cathode-ray tube. The mass of the proton was determined in the same manner as was the mass of the electron. The mass of the proton was found to be 1.67×10^{-27} kg. Heavier ions produced by stripping an electron from gases such as helium, neon, and argon were measured by a similar method.

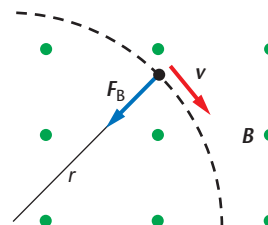
Example Problem

Path of an Electron in a Magnetic Field

An electron of mass 9.11×10^{-31} kg moves through a cathode-ray tube with a speed of 2.0×10^5 m/s across and 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 followed by the electron?

Sketch the Problem

- Draw the path of the electron, and label the velocity, $\mathbf{v}$.
- 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.



Calculate Your Answer

Known:

$$v = 2.0 \times 10^5 \text{ m/s}$$

$$B = 3.5 \times 10^{-2} \text{ T}$$

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

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

Strategy:

Solve for the radius using the equation obtained from Newton's second law of motion.

Unknown:

$$r = ?$$

Calculations:

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

$$r = \frac{mv}{Bq} = \frac{(9.11 \times 10^{-31} \text{ kg})(2.0 \times 10^5 \text{ m/s})}{(3.5 \times 10^{-2} \text{ T})(1.60 \times 10^{-19} \text{ C})}$$

$$r = 3.3 \times 10^{-5} \text{ m}$$

Check Your Answer

- Are the units correct? The radius of the circular path is a length measurement, the meter.

Practice Problems

Assume that the direction of all moving charged particles is perpendicular to the uniform magnetic field.

1. Protons passing without deflection through a magnetic field of 0.60 T are balanced by a $4.5 \times 10^3\text{-N/C}$ electric field. What is the speed of the moving protons?
2. A proton moves at a speed of $7.5 \times 10^3 \text{ m/s}$ as it passes through a 0.60-T magnetic field. Find the radius of the circular path. The charge carried by the proton is equal to that of the electron, but it is positive.
3. Electrons move through a $6.0 \times 10^{-2}\text{-T}$ magnetic field balanced by a $3.0 \times 10^3\text{-N/C}$ electric field. What is the speed of the electrons?
4. Calculate the radius of the circular path that the electrons in Practice Problem 3 follow in the absence of the electric field.

The Mass Spectrometer

When Thomson put neon gas into his tube, he found two dots on the screen instead of one, and thus two values for q/m . He ultimately concluded that atoms of the same element could have the same chemical properties but different masses; he had shown the existence of **isotopes**, a possibility first proposed by chemist Frederick Soddy.

The masses of positive ions can be measured precisely by using a **mass spectrometer**, an adaptation of the Thomson tube. It is used to

Pocket Lab

Rolling Along



Place a small ball of clay under one end of a grooved ruler to make a ramp. Roll a 6-mm-diameter steel ball down the ramp and along the tabletop. Place a strong magnet near the path of the ball so that the ball will curve, but not hit the magnet. Predict what will happen to the path when the ball is started higher or lower on the ramp. Try it.

Analyze and Conclude Is this consistent for a charged particle moving through a magnetic field?

determine the charge-to-mass ratios of gases and of materials that can be heated to form gases. The material under investigation is called the ion source. In the ion source, accelerated electrons strike the gas atoms, knocking off electrons and thus forming positive gas ions. A potential difference, V , between the electrodes produces an electric field that accelerates the ions. One type of mass spectrometer is shown in **Figure 26–3**.

To select ions with a specific velocity, the ions first are passed through electric and magnetic deflecting fields, as in the Thomson tube. The ions that go through undeflected move into a region with a uniform magnetic field. There they follow a circular path, which has a radius that can be obtained from Newton's second law: $Bqv = mv^2/r$. Solving for r yields the following equation.

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

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

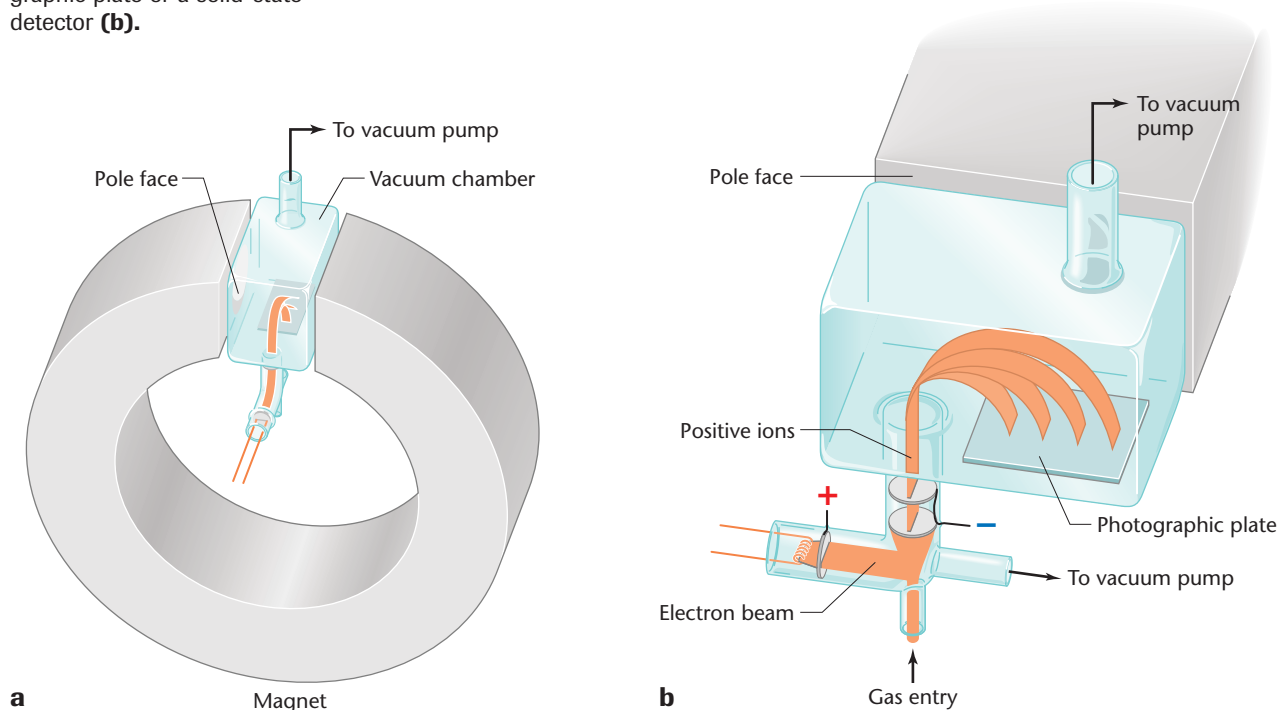
$$K = 1/2mv^2 = qV$$

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

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

$$r = \frac{mv}{qB} = \frac{m}{qB} \sqrt{\frac{2qV}{m}} = \frac{1}{B} \sqrt{\frac{2Vm}{q}}$$

FIGURE 26–3 The mass spectrometer is used extensively to analyze isotopes of an element. Inside the spectrometer, a magnet causes the positive ions 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)**.



From this equation, the charge-to-mass ratio of the ion is determined.

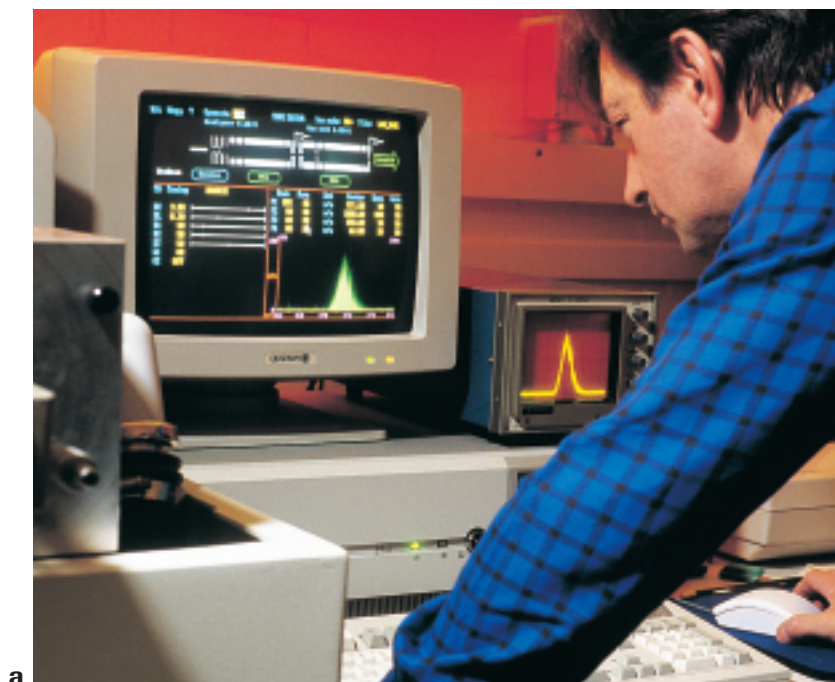
Charge-to-Mass Ratio in a Mass Spectrometer

$$Br = \sqrt{\frac{2mV}{q}}, \text{ so } \frac{q}{m} = \frac{2V}{B^2 r^2}$$

In one type of mass spectrometer, the ions hit a photographic film, where they leave a mark. The radius, r , is found by measuring the distance between the mark and the slit in the electrode. This distance is twice the radius of the circular path. **Figure 26–4** shows marks on film from the four isotopes of the element chromium. The isotope with mass number 52 makes the darkest mark, showing that most chromium atoms have this mass.

All of the chromium ions that hit the film have the same charge. The charge depends on how many electrons were removed in the ion source. It takes more-energetic electrons to remove a second electron from the gas atoms. For low electron energies, only one electron is removed from an atom. When the energy is increased, however, both singly and doubly charged ions are produced. In this way, the operator of the mass spectrometer can choose the charge on the ion.

Mass spectrometers are extremely versatile tools. For example, they can be used to separate isotopes of atoms such as uranium. Instead of film, cups are used to collect the separated isotopes. In another application, chemists use a mass spectrometer (often called an MS) as a very sensitive tool to find small amounts of molecules in a sample. Amounts as small as one molecule in 10 billion molecules can be identified. Investigators detect the ions using electronic devices and are able to separate ions with mass differences of one ten-thousandth of one percent.



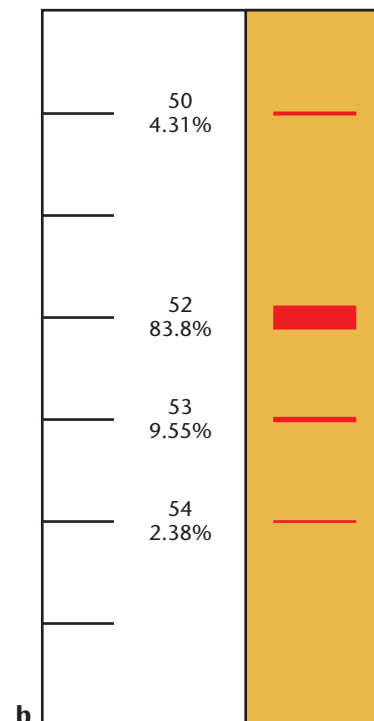
a

Math Handbook

T

To review **solving equations**, see the Math Handbook, Appendix A, page 740.

FIGURE 26–4 The mass spectrometer **(a)** is widely used to determine relative concentrations of various isotopes of an element. This spectrometer's computer display is used to check sensitivity and resolution prior to analysis. During analysis, marks are left on a film **(b)** by ^{50}Cr , ^{52}Cr , ^{53}Cr , and ^{54}Cr . Note that the weight of the mark is proportional to the percentage of the isotope in the element.



b

Example Problem

The Mass of a Neon Atom

The operator of a mass spectrometer produces a beam of doubly ionized neon atoms. They are first accelerated by a potential difference of 34 V. In a 0.050-T magnetic field, the radius of the path of the ions is 53 mm. Find the mass of the neon atom as a whole number of proton masses.

Sketch the Problem

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

Calculate Your Answer

Known:

$$V = 34 \text{ V}$$

$$B = 0.050 \text{ T}$$

$$r = 0.053 \text{ m}$$

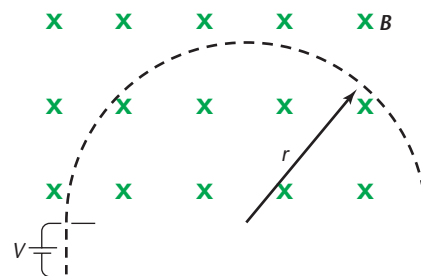
$$q = 2(1.60 \times 10^{-19} \text{ C}) = 3.20 \times 10^{-19} \text{ C}$$

$$m_{\text{proton}} = 1.67 \times 10^{-27} \text{ kg}$$

Unknown:

$$m_{\text{neon}} = ?$$

$$N_{\text{protons}} = ?$$



Strategy:

Find the charge-to-mass ratio using the equation at the right.

Because the charge is known, the mass can be found.

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

Calculations:

$$\frac{q}{m} = \frac{2V}{B^2 r^2}, \text{ so } m = \frac{qB^2 r^2}{2V}$$

$$m_{\text{neon}} = \frac{(3.20 \times 10^{-19} \text{ C})(0.050 \text{ T})^2(0.053 \text{ m})^2}{2(34 \text{ V})}$$

$$= 3.3 \times 10^{-26} \text{ kg}$$

$$N_{\text{protons}} = \frac{m_{\text{neon}}}{m_{\text{proton}}} = \frac{(3.3 \times 10^{-26} \text{ kg})}{(1.67 \times 10^{-27} \text{ kg/proton})}$$

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

Check Your Answer

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

Practice Problems

5. A stream of singly ionized lithium atoms is not deflected as it passes through a 1.5×10^{-3} -T magnetic field perpendicular to a 6.0×10^2 -V/m electric field.

- a. What is the speed of the lithium atoms as they pass through the crossed fields?
 - b. The lithium atoms move into a magnetic field of 0.18 T. They follow a circular path of radius 0.165 m. What is the mass of a lithium atom?
6. A mass spectrometer analyzes and gives data for a beam of doubly ionized argon atoms. The values are $q = 2(1.60 \times 10^{-19} \text{ C})$, $B = 5.0 \times 10^{-2} \text{ T}$, $r = 0.106 \text{ m}$, and $V = 66.0 \text{ V}$. Find the mass of an argon atom.
 7. A beam of singly ionized oxygen atoms is sent through a mass spectrometer. The values are $B = 7.2 \times 10^{-2} \text{ T}$, $q = 1.60 \times 10^{-19} \text{ C}$, $r = 0.085 \text{ m}$, and $V = 110 \text{ V}$. Find the mass of an oxygen atom.
 8. You found the mass of a neon isotope in the last Example Problem. Another neon isotope has a mass of 22 proton masses. How far from the first isotope would these ions land on the photographic film?

F.Y.I.

The Federal Communications Commission 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.

26.1 Section Review

1. Consider what changes Thomson would have had to make to accelerate protons rather than electrons in his cathode-ray tube.
 - a. To select particles of the same velocity, would the ratio E/B have to be changed?
 - b. For the deflection caused by the magnetic field alone to remain the same, would the B field have to be made smaller or larger? Explain.
2. As Thomson raised the energy of the electrons producing the ions in his tube, he found ions with two positive elementary charges rather than just one. How would he have recognized this?
3. 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 magnetic field have to be changed for them to hit the film?
4. **Critical Thinking** Thomson did not know the number of electrons in the atoms. With most atoms, he found that, as he raised the energy of the electrons that produced ions, he would first get ions with one electron missing, then ions with two electrons missing, and so on. With hydrogen, however, he could never remove more than one electron. What could he then conclude about the positive charge of the hydrogen atom?



Simulating a Mass Spectrometer

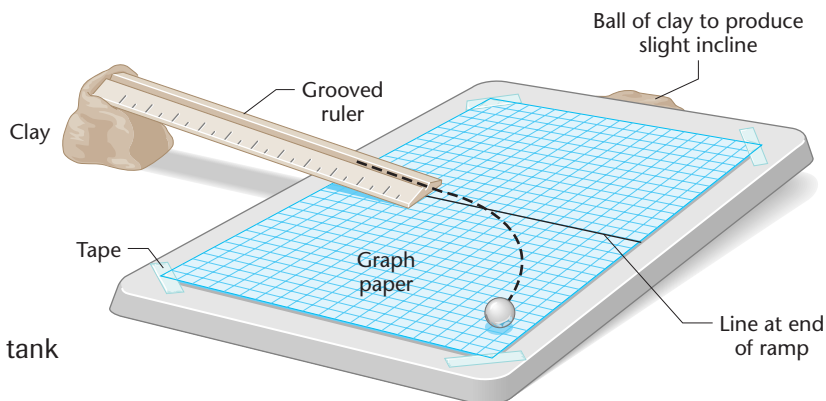
Problem

How can you simulate the working parts of a mass spectrometer?

Materials



2 balls of clay
6-mm steel ball
graph paper
masking tape
2 permanent magnets
cafeteria tray or glass wave tank
grooved ruler
glass marble



Procedure

1. Build the apparatus as shown in the diagram. Place a ball of clay under one side of the wave tank so that the tank is slightly sloped.
2. Make a test trial, allowing the steel ball to roll down the track. The ball should follow a curved path similar to the one shown in the diagram when it is started halfway up the ruler.
3. Starting from the same spot on the ruler, roll the steel ball down the track three times. Mark the positions where the ball crosses the far side of the graph paper.
4. Place the permanent magnets on the paper so they pull the ball slightly toward the high end of the slope. Adjust the magnets so the ball follows a straight path across the graph paper, as shown in the diagram.
5. Releasing the ball from the same spot on the ruler, repeat step 3.
6. When you have completed the lab, dispose of or recycle appropriate materials. Put away materials that can be reused.

Data and Observations

1. Describe the path of the ball in step 3.
2. Describe the path of the ball in step 5.

Analyze and Conclude

1. **Thinking Critically** In this model, you used gravity to simulate the electric field of a mass spectrometer. How could the electric field in this model be varied?
2. **Analyzing Data** What happens to the path as the magnet is brought closer to the path of the ball? Why?
3. **Thinking Critically** If you release the ball from a higher location, the ball will leave the ruler with more speed. In this case, the path will curve less, even though the force on the ball is the same. Why?

Apply

1. Predict what would happen to a 6-mm ball that had the same mass, but less or no iron content. Explain your prediction. Test it.

Electric and Magnetic Fields in Space



Signals emanating from galaxies, satellites, and television stations are electromagnetic waves.

The properties of the electric and magnetic fields that constitute these waves were studied during most of the nineteenth century. In 1820, Oersted discovered that currents produce magnetic fields, and 11 years later, Faraday discovered induction. In the 1860s, Maxwell predicted that even without wires, electric fields changing in time cause magnetic fields, and that the magnetic fields changing in time produce electric fields. The result of this coupling is energy transmitted across empty space in the form of electromagnetic waves. Maxwell's theory led to a complete description of electricity and magnetism. It also gave us radio, television, and many other devices that have become part of our daily lives.

Electromagnetic Waves

Oersted found that an electric current in a conductor produces a magnetic field. Changing the current changes the magnetic field, and, as Faraday discovered, changing the magnetic field can induce an electric current in a wire. Furthermore, the current-producing electric fields exist even without a wire, as illustrated in **Figure 26–5a**. Thus, a changing magnetic field produces a changing electric field. The field lines of the induced electric field will be closed loops, because unlike an electrostatic field, there are no charges on which the lines begin or end.

In 1860, Maxwell postulated that the opposite also is true. A changing electric field produces a changing magnetic field, as shown in **Figure 26–5b**. Maxwell suggested that charges were not necessary; the changing electric field alone would produce the magnetic field.

OBJECTIVES

- **Describe** how electric and magnetic fields can produce more electric and magnetic fields.
- **Explain** how accelerated charges produce electromagnetic waves.
- **Explain** the process by which electromagnetic waves are detected.

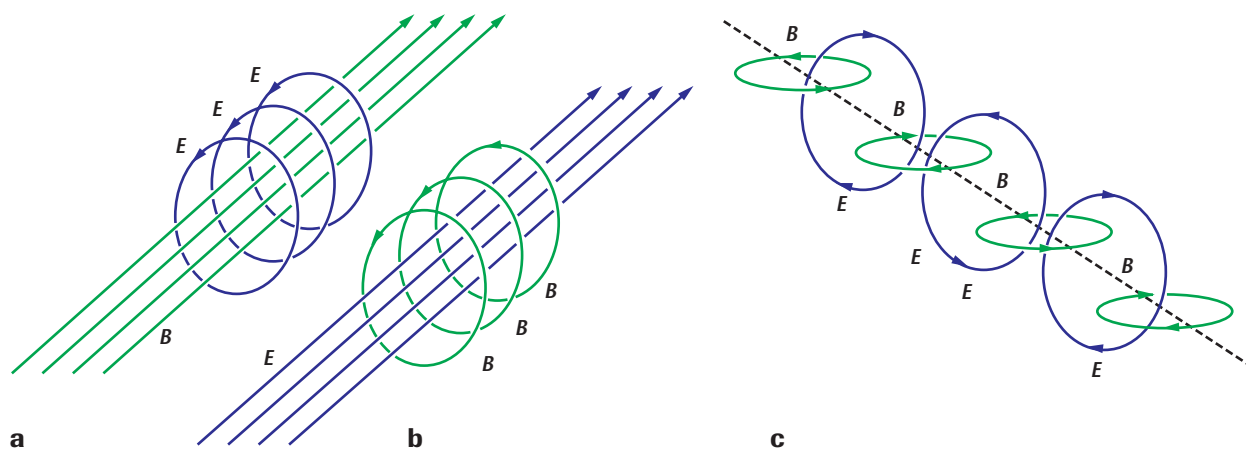


FIGURE 26–5 These diagrams represent an induced electric field **(a)**, a magnetic field **(b)**, and both electric and magnetic fields **(c)**.

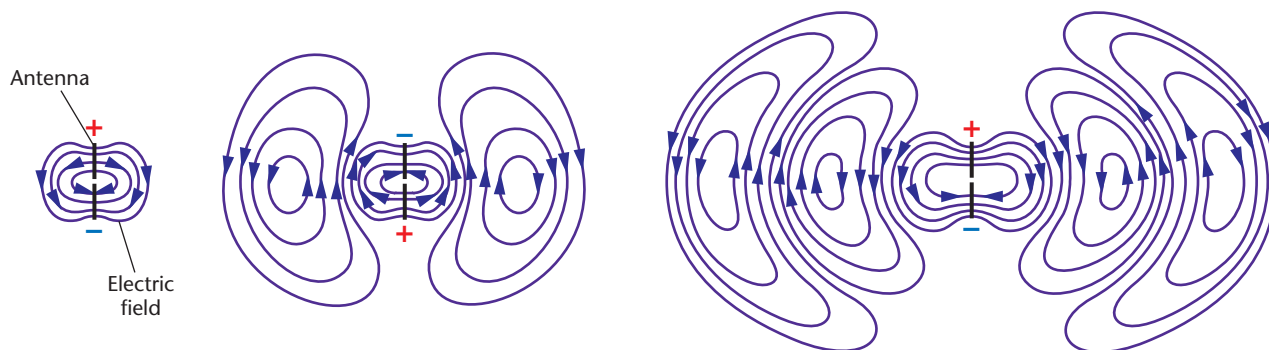


FIGURE 26-6 The changing current in the antenna generates a changing electric field. The changing electric field generates a changing magnetic field (not shown).

Maxwell then predicted that either accelerating charges or changing magnetic fields would produce electric and magnetic fields that move through space, **Figure 26-5c**. The combined fields are called an **electromagnetic wave**. The speed at which the wave moves, calculated Maxwell, was the speed of light, 3.00×10^8 m/s, as measured by Fizeau in 1849. Not only were electricity and magnetism linked, but also, optics, the study of light, became a branch of the study of electricity and magnetism. Heinrich Hertz (1857–1894), a German physicist, demonstrated experimentally in 1887 that Maxwell’s theory was correct.

Figure 26-6 shows the formation of an electromagnetic wave. A wire, called an **antenna**, is connected to an alternating current (AC) source. The source produces changing currents in the antenna that alternate at the frequency of the AC source. The changing currents generate a changing electric field that moves outward from the antenna. There is also a changing magnetic field perpendicular to the page that is generated by the changing electric field, although the magnetic field is not shown in the figure. The electromagnetic waves spread out in space, moving at the speed of light.

If you stood to the right of the antenna as the waves approached, you could imagine the electric and magnetic fields changing in time, as in **Figure 26-7**. The electric field oscillates, first up, then down. The magnetic field oscillates at right angles to the electric field. The two fields are also at right angles to the direction of the motion of the wave. An electromagnetic wave produced by an antenna such as the one shown in **Figure 26-6** is polarized; that is, the electric field is always parallel to the direction of the antenna wires.

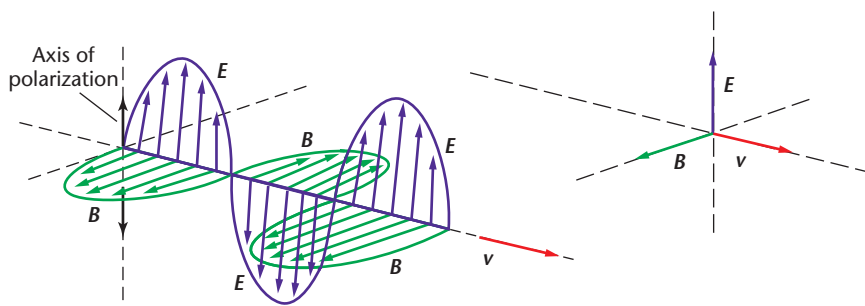


FIGURE 26-7 Portions of the electric and magnetic fields generated by an antenna might look like this at an instant in time.

Pocket Lab

Catching the Wave



When you listen to your radio, you are hearing the information that is carried by electromagnetic waves. Many electronic and electrical devices produce low-frequency electromagnetic waves. Use a telephone pickup coil along with an amplifier to try to pick up signals from such devices as a television, computer, light, burning candle, coffee maker, or vacuum cleaner.

Analyzing Data Describe and interpret your results.

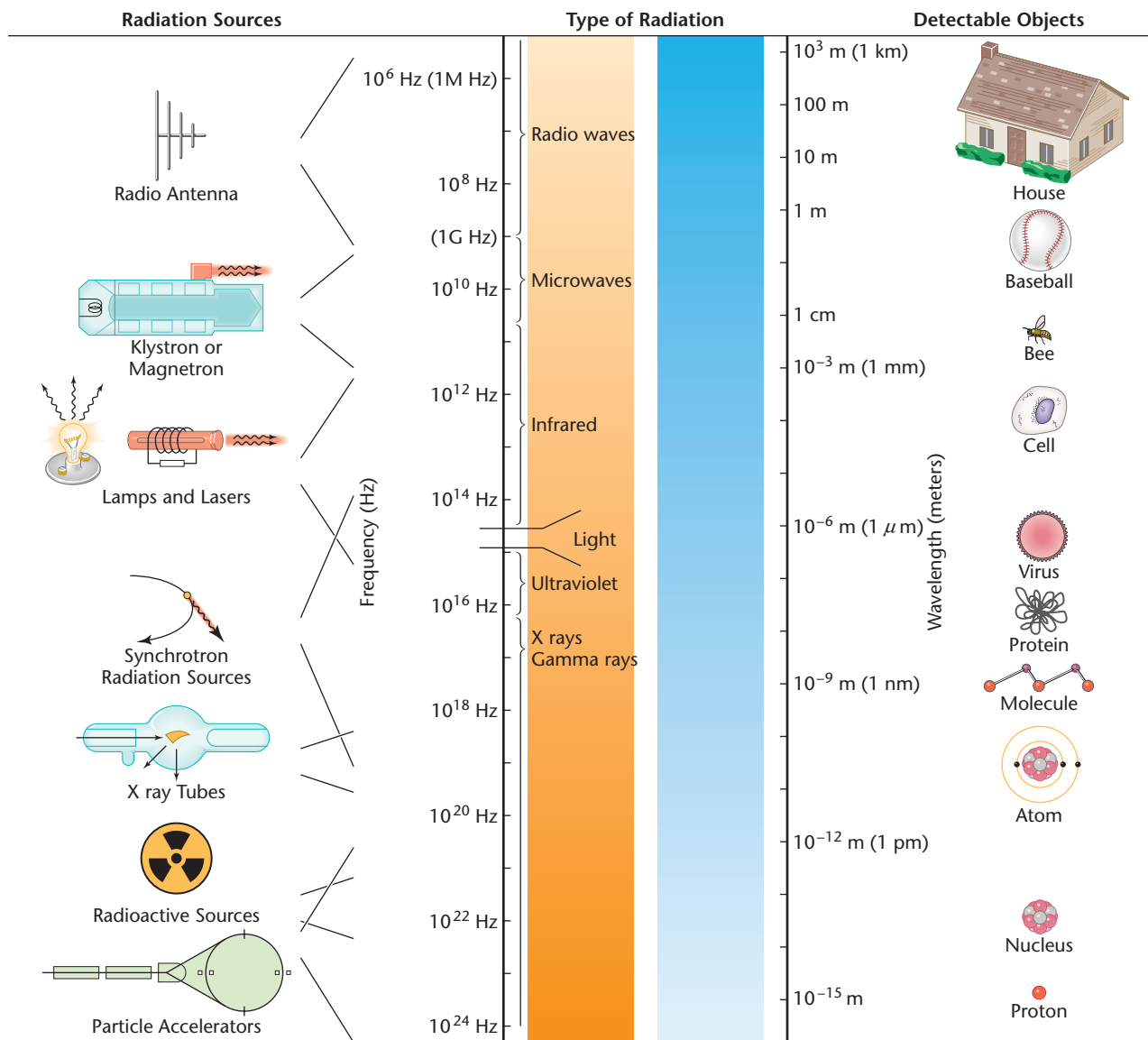


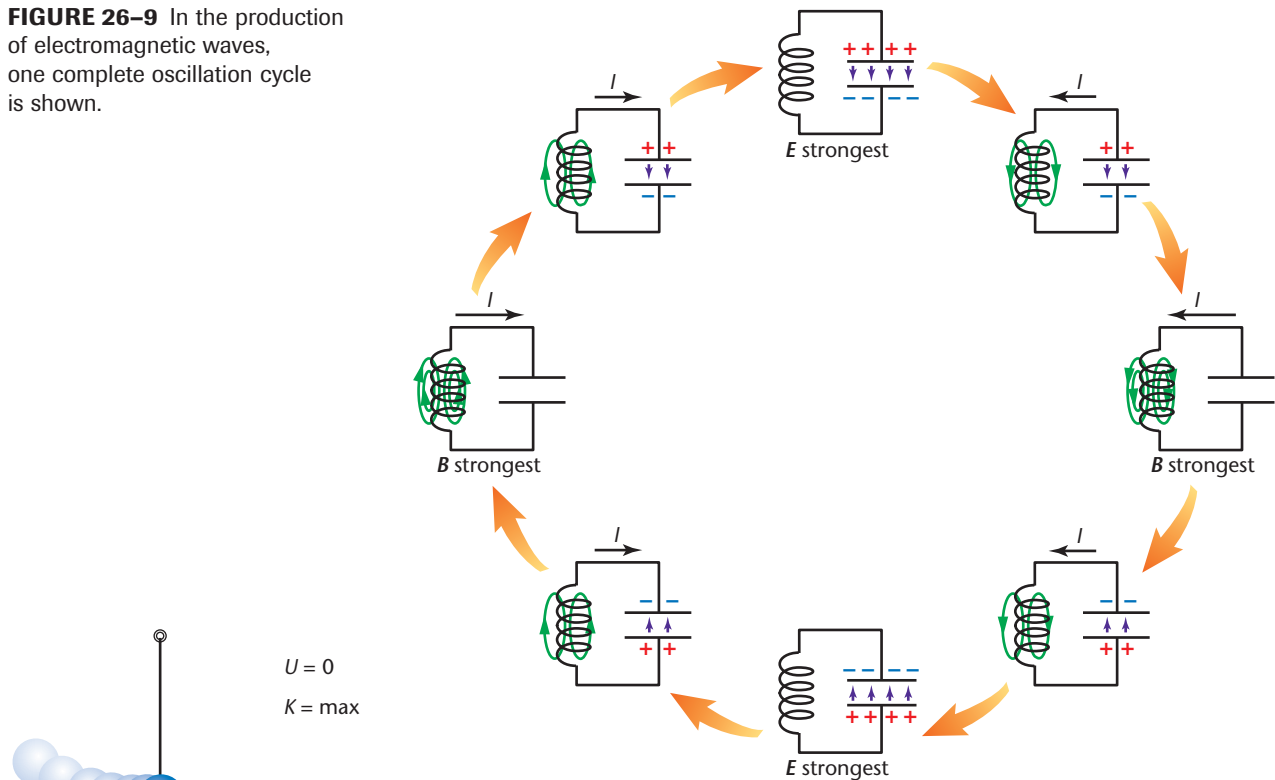
FIGURE 26–8 Representative examples of various types of electromagnetic radiation and their wavelengths are shown here.

Production of Electromagnetic Waves

Electromagnetic waves can be generated over a wide range of frequencies. **Figure 26–8** shows the electromagnetic spectrum. As you have learned, the AC generator is one method of creating the oscillating fields in the antenna. The frequency of the wave can be changed by varying the speed at which the generator is rotated. The highest frequency that can be generated in this way is about 1000 Hz.

Using a coil and capacitor The most common method of generating waves of higher frequencies is to use a coil and 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

FIGURE 26-9 In the production of electromagnetic waves, one complete oscillation cycle is shown.



removed, the capacitor discharges, and the stored electrons flow through the coil, creating a magnetic field. After the capacitor has discharged, the magnetic field of the coil collapses. A back-EMF develops that recharges the capacitor, this time in the opposite direction. The capacitor again discharges, and the process is repeated. One complete oscillation cycle is shown in **Figure 26-9**. Recall that the number of oscillations each second is called the frequency, which depends on the size of the capacitor and the coil. The antenna, connected across the capacitor, extends the fields of the capacitor into space.

A pendulum analogy, illustrated in **Figure 26-10**, can help you understand the coil and capacitor circuit. The electrons in the coil and capacitor are represented by the pendulum bob. The bob moves fastest when its displacement from vertical is zero. This is similar to the largest current flowing in the coil when the charge on the capacitor is zero. When the bob is at its greatest angle, its displacement from the vertical is largest, and it has zero velocity. This position is like the instant when the capacitor holds the largest charge and the current through the coil is zero.

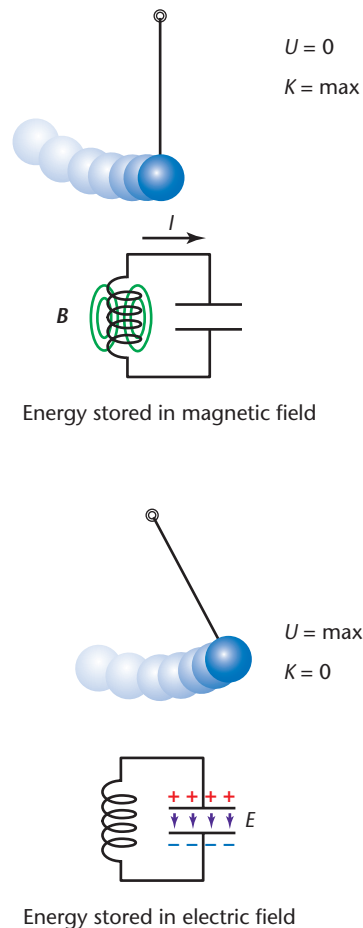


FIGURE 26-10 A pendulum is analogous to the action of electrons in a coil and capacitor combination.

Energy considerations The pendulum model also can be used to describe energy. The potential energy of the pendulum is largest when its displacement is greatest. The kinetic energy is largest when the velocity is greatest. The sum of the potential and kinetic energies—the total energy—is constant. 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 in the electric field. The total energy—the sum of the magnetic field energy, the electric field energy, the thermal losses, and the energy carried away by the electromagnetic waves being generated—is constant. Energy carried, or radiated, in the form of electromagnetic waves is frequently called **electromagnetic radiation**.

Just as the pendulum will eventually stop swinging if it is left alone, the oscillations in a coil and capacitor also will die out because of resistance in the circuit, unless energy is added to the circuit. Gentle pushes, applied at the correct times, will keep a pendulum moving. The swing of largest amplitude occurs when the frequency of pushing is the same as the frequency of swinging. This is the condition of resonance, which was discussed in Chapter 6. Similarly, voltage pulses applied to the coil and capacitor circuit at the right frequency keep the oscillations going. One way of doing this is to add a second coil to form a transformer, as in **Figure 26–11**. The AC 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.

Increasing the oscillation frequency To increase the oscillation frequency, the size of the coil and capacitor must be made smaller. Above 1000 MHz, individual coils and capacitors will not work. For these electromagnetic waves, called microwaves, a rectangular box called a resonant cavity acts as both a coil and a capacitor. The size of the box determines the frequency of oscillation. Such a cavity is found in every microwave oven.

At frequencies of infrared waves, the size of resonant cavities would have to be reduced to the size of molecules. The oscillating electrons that produce infrared waves are, in fact, within the molecules. Visible and ultraviolet waves are generated by electrons within atoms.

High-frequency waves, such as X rays and gamma waves, are the result of accelerating charges in the nucleus of an atom. Most electromagnetic waves arise from accelerated charges, and all travel at the speed of light.

Piezoelectricity Coils and capacitors are not the only method of generating oscillation voltages. Quartz crystals have a property called **piezoelectricity**: they bend or deform when a voltage is applied across them. Just as a piece of metal will vibrate at a specific frequency when it is bent and released, so too will a quartz crystal. A crystal can be cut so that it will vibrate at a specific desired frequency. An applied voltage bends it so that it starts vibrating. The piezoelectric property also generates an *EMF* when the crystal is bent. 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. Quartz crystals are used in wrist-watches because the frequency of vibration is so constant.

Pocket Lab

More Radio Stuff



Radio stations broadcast with tremendous power from tall towers. Would it be possible to make your own radio transmitter and receiver? Try this activity to find out. Pop your favorite tape into a tape player, or tune your portable radio to a strong local AM station. Next, put a miniplug into the earphone jack, and attach the two leads to the ends of an air core solenoid. Put a second miniplug into a miniamp speaker, and attach the leads to the ends of a second air core solenoid. Turn the power on for the miniamp speaker, and listen for the sound.

Make a Hypothesis Make a hypothesis explaining why this lab works. Try changing the distance between the solenoids. Explain your results.

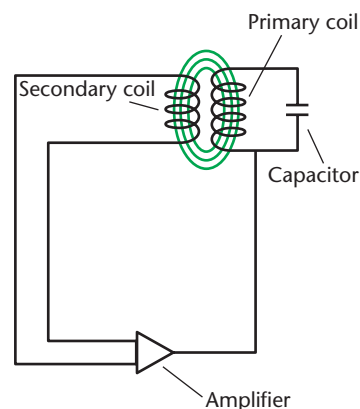


FIGURE 26–11 The amplified pulse from the secondary coil is in resonance with the coil and capacitor circuit and keeps the oscillations going.

How It Works

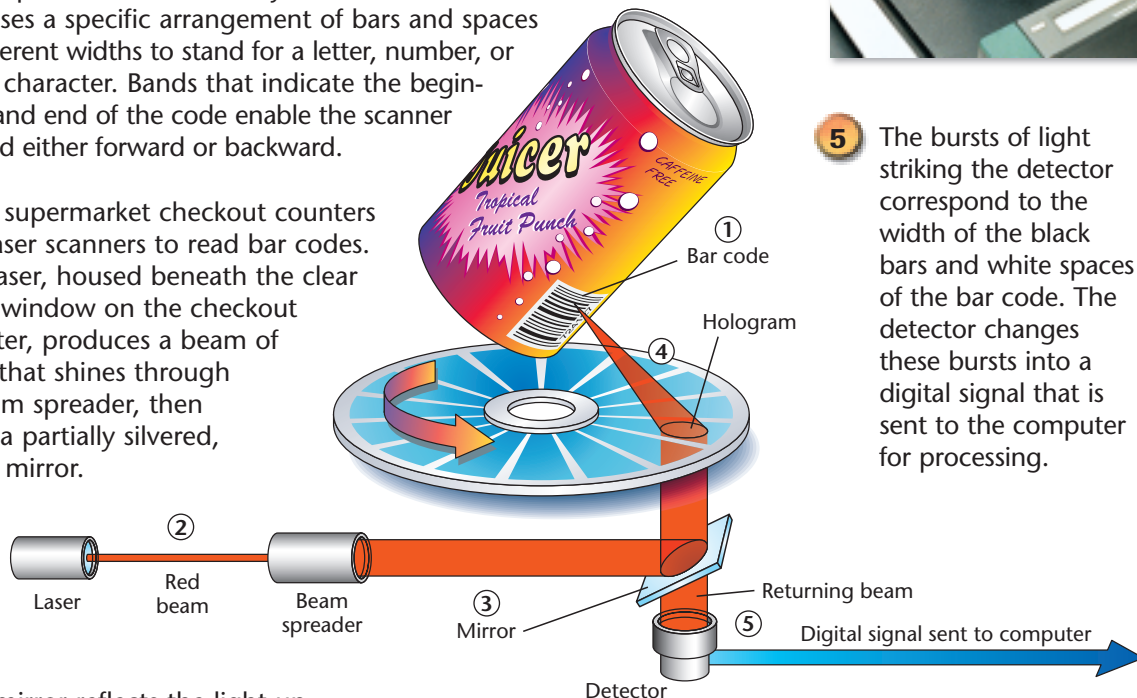
Bar-Code Scanners

A bar-code scanner uses light to “read” a code made up of bands of black and white bars. The computer links the code with data about the bar-coded item. In a supermarket, for example, the computer can display and print the name and price of the item, record the sale for the store’s records, and even keep track of how many of those items remain in stock.



1 Bar codes consist of a series of alternating black bars and white spaces. There are many different bar codes. Each one uses a specific arrangement of bars and spaces of different widths to stand for a letter, number, or other character. Bands that indicate the beginning and end of the code enable the scanner to read either forward or backward.

2 Most supermarket checkout counters use laser scanners to read bar codes. The laser, housed beneath the clear glass window on the checkout counter, produces a beam of light that shines through a beam spreader, then onto a partially silvered, tilted mirror.



3 The mirror reflects the light up through a rotating disc. The disc focuses and directs the beam through the scanner window.

4 As the cashier drags each bar-coded item across the scanner window, the laser light scans the bar code. Light that hits the spaces between the black bars is reflected back through the scanner window, through the mirror, and onto a detector below.

5 The bursts of light striking the detector correspond to the width of the black bars and white spaces of the bar code. The detector changes these bursts into a digital signal that is sent to the computer for processing.

Thinking Critically

1. Review the descriptions of digital versatile discs in Chapter 16 and laser printers in Chapter 20. Compare and contrast the operation of a bar code scanner with these two devices.
2. Research and evaluate the impact on society and the environment of research to develop devices that use electromagnetic waves.

Reception of Electromagnetic Waves

Now let's examine how electromagnetic waves can be detected. When the electric fields in these waves strike another antenna, as shown in **Figure 26–12**, they accelerate the electrons in it. The acceleration is largest when the antenna is turned in the direction of the polarization of the wave; that is, when it is parallel to the direction of the electric fields in the wave. An *EMF* across the terminals of the antenna oscillates at the frequency of the electromagnetic wave. The *EMF* is largest if the length of the antenna is one-half the wavelength of the wave. The antenna then resonates in the same way an open pipe one-half wavelength long resonates with sound waves. For that reason, an antenna designed to receive radio waves is much longer than one designed to receive microwaves.

While a simple wire antenna can detect electromagnetic waves, several wires can be used to increase the detected *EMF*. A television antenna often consists of two or more wires spaced about one-quarter wavelength apart. Electric fields generated in the individual wires form constructive interference patterns that increase the strength of the signal. At very short wavelengths, parabolic dishes reflect the waves, just as parabolic mirrors reflect light waves. Giant parabolic dishes focus waves with wavelengths of 2 to 6 cm on the antennas held by the tripod above the dish.

Selection of waves Radio and television waves transmit information across space. Many different radio and television stations produce 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 coil and capacitor circuit is connected to the antenna. The capacitance is adjusted until the oscillation frequency of the circuit equals the frequency of the desired wave. Only this frequency can cause significant oscillations of the electrons in the circuit. The information carried by the oscillations is then amplified and ultimately drives a loudspeaker. The combination of antenna, coil and capacitor circuit, and amplifier is called a **receiver**.

Energy from waves Waves carry energy as well as information. At microwave and infrared frequencies, the electromagnetic waves accelerate electrons in molecules. The energy of the electromagnetic waves is converted to thermal energy in the molecules. Microwaves cook foods in this way. Infrared waves from the sun produce the warmth you feel on a bright, sunny day.

Light waves can transfer energy to electrons in atoms. In photographic film, this energy causes a chemical reaction. The result is a permanent record of the light reaching the camera from the subject. In the eye, the energy produces a chemical reaction that stimulates a nerve, resulting in a response in the brain that we call vision. At higher frequencies, UV radiation causes many chemical reactions to occur, including those in living cells that produce sunburn and tanning.

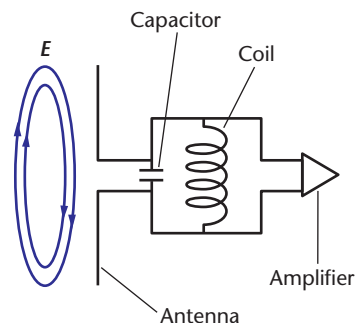


FIGURE 26–12 The changing electric fields from a radio station cause electrons in the antenna to accelerate.

Big Ears

➡ *Answers question from page 602.*



X Rays

In 1895, German physicist Wilhelm Roentgen (1845–1923) 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 a large kinetic energy. The electrons struck the metal anode of the tube. When this happened, Roentgen noted 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 is now known that **X rays** are high-frequency electromagnetic waves. They are produced when electrons are accelerated to high speeds by means of potential differences of 20 000 or more volts. 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 face plate, they cause the colored phosphors to glow. The sudden stopping of the electrons also can produce X rays. The face-plate glass in television screens contains lead to stop the X rays and protect viewers.

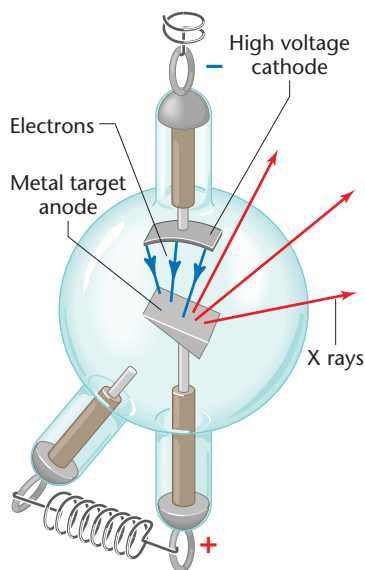


FIGURE 26–13 The metal target in this X-ray tube can be changed to produce X rays of different wavelengths.

26.2 Section Review

1. What was Maxwell's contribution to electromagnetism?
2. What are the characteristics of electromagnetic waves? Do they behave differently than other waves, such as sound waves? Explain.
3. Television antennas normally have the metal rod elements in a horizontal position. From that, what can you deduce about the directions of the electric fields in television signals?
4. 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?
5. **Critical Thinking** Most of the UV radiation from the sun is blocked by the ozone layer in Earth's atmosphere. Scientists have found a thinning of the ozone layer over both Antarctica and the Arctic Ocean. Should we be concerned about this?

CHAPTER 26 REVIEW

Summary

Key Terms

26.1

- isotope
- mass spectrometer

26.2

- electromagnetic wave
- antenna
- electromagnetic radiation
- piezoelectricity
- receiver
- X ray

26.1 Interaction Between Electric and Magnetic Fields and Matter

- The ratio of charge to mass of the electron was measured by J. J. Thomson using balanced electric and magnetic fields in a cathode-ray tube.
- An electron's mass can be found by combining Thomson's result with Millikan's measurement of the electron's charge.
- The mass spectrometer uses both electric and magnetic fields to measure the masses of ionized atoms and molecules.

26.2 Electric and Magnetic Fields in Space

- Electromagnetic waves are coupled, changing electric and magnetic fields that move through space.
- Changing currents in an antenna generate electromagnetic waves.
- The frequency of oscillating currents can be selected by a resonating coil and capacitor circuit.

- Electromagnetic waves can be detected by the *EMF* they produce in an antenna. 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, producing thermal energy.
- When high-energy electrons strike an anode in an evacuated tube, their kinetic energies are converted to electromagnetic waves of very high energy called X rays.



Key Equations

26.1

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

Reviewing Concepts

Section 26.1

1. What is the mass of an electron? What is its charge?
2. What are isotopes?

Section 26.2

3. The direction of an induced magnetic field is always at what angle to the changing electric field?
4. Like all waves, microwaves can be transmitted, reflected, and absorbed. Why can soup be heated in a ceramic mug but not in a metal pan in a microwave oven? Why does the mug's handle not get as hot as the soup?
5. Why must an AC generator be used to propagate electromagnetic waves? If a DC generator were used, when would it create electromagnetic waves?
6. A vertical antenna wire transmits radio waves. Sketch the antenna and the electric and magnetic fields it creates.
7. What happens to quartz crystals when a voltage is placed across them?
8. Car radio antennas are vertical. What is the direction of the electric fields they detect?
9. How does an antenna receiving circuit select electromagnetic radio waves of a certain frequency and reject all others?

Applying Concepts

10. The electrons in a Thomson tube travel from left to right. Which deflection plate should be charged positively to bend the electron beam upward?
11. The electron beam in question 10 has a magnetic field to make the beam path straight. What would be the direction of the magnetic field needed to bend the beam downward?
12. Show that the units of E/B are the same as the units for velocity.
13. A mass spectrometer operates on neon ions. What is the direction of the magnetic field needed to bend the beam in a clockwise semicircle?
14. Charged particles are moving through an electric field and a magnetic field that are perpendicular to each other. Suppose you adjust the fields so that a certain ion, with the correct velocity, passes without deflection. Then, another ion with the same velocity but a different mass enters the fields. Describe the path of the second ion.
15. If the sign of the charge on the particle in question 14 is changed from positive to negative, do the directions of either or both of the two fields have to be changed to keep the particle undeflected? Explain.
16. Do radio waves, light, or X rays have the largest
a. wavelength? b. frequency? c. velocity?
17. 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?
18. 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?
19. The electrons in a beam move at 2.8×10^8 m/s in an electric field of 1.4×10^4 N/C. What value must the magnetic field have if the electrons pass through the crossed fields undeflected?
20. A proton moves across a 0.36-T magnetic field in a circular path of radius 0.20 m. What is the speed of the proton?
21. Electrons move across a 4.0-mT magnetic field. They follow a circular path with radius 2.0 cm.
a. What is their speed?
b. An electric field is applied perpendicularly to the magnetic field. The electrons then follow a straight-line path. Find the magnitude of the electric field.
22. 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?
23. A proton enters a magnetic field of 6.4×10^{-2} T with a speed of 4.5×10^4 m/s. What is the circumference of its circular path?
24. A 3.0×10^{-2} -T magnetic field in a mass spectrometer causes an isotope of sodium to move in a circular path with a radius of 0.081 m. If the ions have a single positive charge and are moving with a speed of 1.0×10^4 m/s, what is the isotope's mass?
25. An alpha particle, a doubly ionized helium atom, has a mass of 6.7×10^{-27} kg and is accelerated by a voltage of 1.0 kV. If a uniform magnetic field of 6.5×10^{-2} T is maintained on the alpha particle, what will be the particle's radius of curvature?
26. 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?
27. A mass spectrometer yields the following data for a beam of doubly ionized sodium atoms:
 $B = 8.0 \times 10^{-2}$ T, $q = 2(1.60 \times 10^{-19}$ C),
 $r = 0.077$ m, and $V = 156$ V. Calculate the mass of a sodium atom.
28. An alpha particle has a mass of approximately 6.6×10^{-27} kg and bears a double elementary positive charge. Such a particle is observed to move through a 2.0-T magnetic field along a path of radius 0.15 m.

Problems

Section 26.1

19. A beam of ions passes undeflected through a pair of crossed electric and magnetic fields. E is 6.0×10^5 N/C and B is 3.0×10^{-3} T. What is the ions' speed?
20. 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

- 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?
31. In a mass spectrometer, ionized silicon atoms have curvatures with radii of 16.23 cm and 17.97 cm. If the smaller radius corresponds to a mass of 28 proton masses, what is the mass of the other silicon isotope?
32. 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?

Section 26.2

33. The radio waves reflected by a parabolic dish are 2.0 cm long. How long should the antenna be that detects the waves?
34. The difference in potential between the cathode and anode of a spark plug is 1.0×10^4 V.
- a. What energy does an electron give up as it passes between the electrodes?
 - b. One-fourth of the energy given up by the electron is converted to electromagnetic radiation. The frequency of the wave is related to the energy by the equation $E = hf$, where h is Planck's constant, 6.6×10^{-34} J/Hz. What is the frequency of the waves?



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

Critical Thinking Problems

35. H.G. Wells wrote a science fiction book called *The Invisible Man*, in which a man drinks a potion and becomes invisible, although he retains all of his other faculties. Explain why it wouldn't be possible for an invisible person to be able to see.
36. 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 molecules of 175 proton masses from those

with 176 proton masses, but the spacing between adjacent cells in your detector is 0.1 mm. The molecules must have been accelerated by a potential difference of at least 500 volts to be detected. What are some of the values of V , B , and r that your apparatus should have?

Going Further

Project Experiment with the production and detection of electromagnetic waves using two boom boxes or one radio or tape player with an earphone jack and another with a microphone input jack. You will need two plugs fitting the jacks that have two wires to which you can make contact. The boom box with the plug into the earphone jack will generate electromagnetic waves; the boom box with the plug into the microphone jack will detect them. To create and detect electric fields, connect each wire coming from the earphone plug to a soda can. Stand the soda cans side-by-side about 10 cm apart. **CAUTION:** Do not allow any of the cans to touch. Use a second pair of cans connected to the microphone plug. Turn both volume controls up high. See how far you can transmit electromagnetic waves from one pair of cans to the other. You can replace one or both pairs of cans with a coil of wire of at least 100 turns and about 20 cm in diameter. You then will be generating and/or detecting magnetic fields. These electromagnetic waves have frequencies equal to those of the sound waves you generated. What are their wavelengths? Interpret the role of frequency, wavelength, and energy in radio transmissions and related technology development.

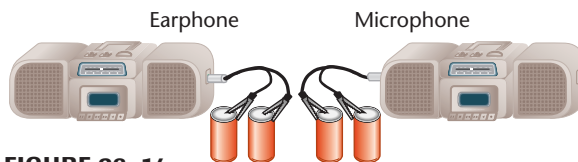


FIGURE 26-14

PHYSICS
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